IRE Transactions

ON VEHICULAR COMMUNICATIONS

J. Fink
N&G
Ew

PGVC-7 DECEMBER, 1956

TABLE OF CONTENTS

*WESCON Papers**

Los Angeles Chapter Paper

*Presented at WESCON Convention, August 21-24, 1956, Los Angeles, California.

PUBLISHED BY THE

PROFESSIONAL GROUP ON VEHICULAR COMMUNICATIONS

IRE PROFESSIONAL GROUP ON VEHICULAR COMMUNICATIONS

The Professional Group on Vehicular Communications is an organization, within the framework of the IRE, of members with principal professional interest in Vehicular Communications. All members of the IRE are eligible for membership in the Group and will receive all Group publications upon payment of prescribed assessments.

Annual Assessment: $2.00

IRE TRANSACTIONS®

on Vehicular Communications

Published by the Institute of Radio Engineers, Inc., for the Professional Group on Vehicular Communications, 1 East 79th Street, New York 21, New York. Responsibility for the contents rests upon the authors, and not upon the IRE, the Group or its members. Individual copies available for sale to IRE-PGVC members at $1.20, to IRE members at $1.80 and to nonmembers at $3.60.

VHF RADIO COORDINATED TRAFFIC LIGHT CONTROL SYSTEM

Elmer W. Hassel
Terminal Equipment Engineering
Technical Products Department
General Electric Company
Syracuse, New York

Summary

Radio coordinated traffic light control permits the elimination of the conventional multi-conductor cable which must tie together all traffic lights in a system. A VHF carrier modulated with audio-frequency control tones permits the radio coordinated system to perform the same as with the use of a cable plus the possibility of gaining additional benefits. All conventional traffic light control equipment may be used without modification. Several systems have been installed with complete success, gaining advantages in cost and flexibility. It may be expected that this form of control will grow rapidly within the next few years.

Introduction

Vehicular traffic-flow problems and the concept of traffic control is not new to any of us. Undoubtedly, everyone has had the distinct desire to be able to push a button on the dashboard of his automobile to cause the red light holding him back to turn green. Since this technique would work for both streets of an intersection, assuming most vehicles would be so equipped, it becomes obvious that such a plan is not workable, at best it would be a random type of control. To help clear up our congested streets, it is necessary to move the maximum number of vehicles through an intersection per unit of time throughout the area of congestion. Our discussion will be in terms of systems of traffic flow and traffic patterns covering an area larger than a single intersection.

The most common technique employed to control a system of traffic lights is the use of a multiple conductor cable which connects each intersection within the system to the master controller as shown in Figure 1.

The master controller applies 115 volt 60 c.p.s. power to one or more conductors in the cable. A string of traffic signals so connected would consist of one master with all the others being slaves. The master is called a Master Controller and the slaves are called Secondary or Local Controllers.

Each Controller has at least one timing unit that determines how long it takes to go from the beginning of Main Street Green to Red to Green again and what portion of that cycle is allocated to Green and Red. This unit is called a DIAL. The dial motor makes one complete revolution for each cycle. There is room in the controller to permit the use of three dial units allowing a choice of three timing cycles (and Red/Green ratio). For instance, Dial 2 might represent normal traffic, Dial 1 heavy inbound traffic and Dial 3 heavy outbound traffic.

To keep a steady progression of traffic as you drive down the street, the first signal should turn Green a few seconds before the second signal and so on down the line. This time delay is called OFFSET and its length is determined by the distance between intersections and the progression rate desired. There are three offsets for each dial unit. Offset is variable and is pre-set by inserting metal tabs in corresponding slots in the timing wheel. We can have a choice of three dials and three offsets per dial.

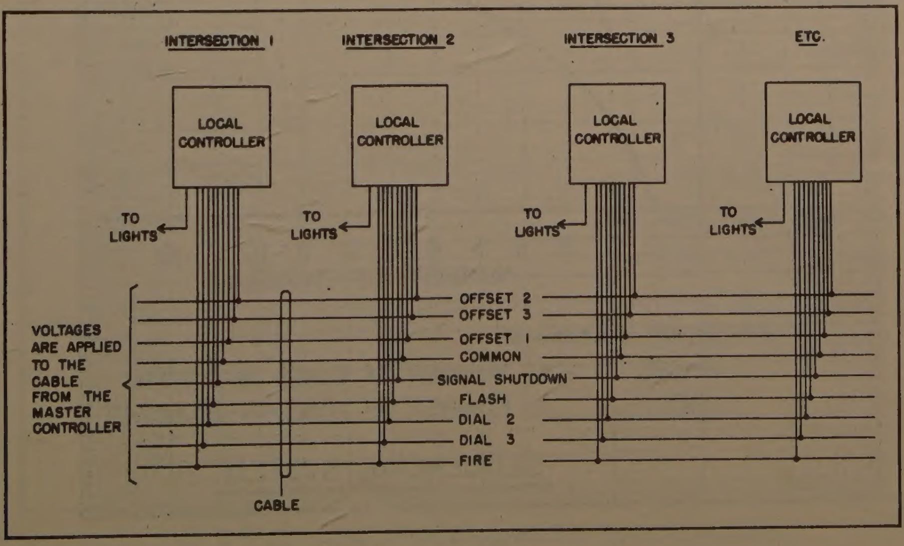

Fig. 1 - Typical interconnected system.

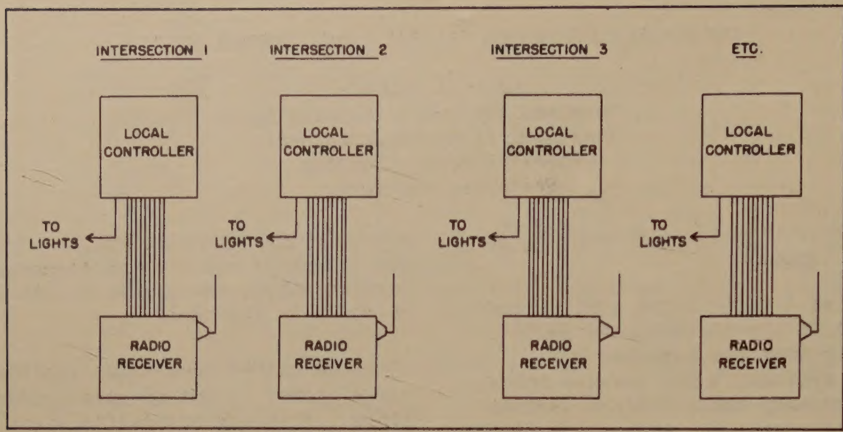

Fig. 2 - Radio interconnected system.

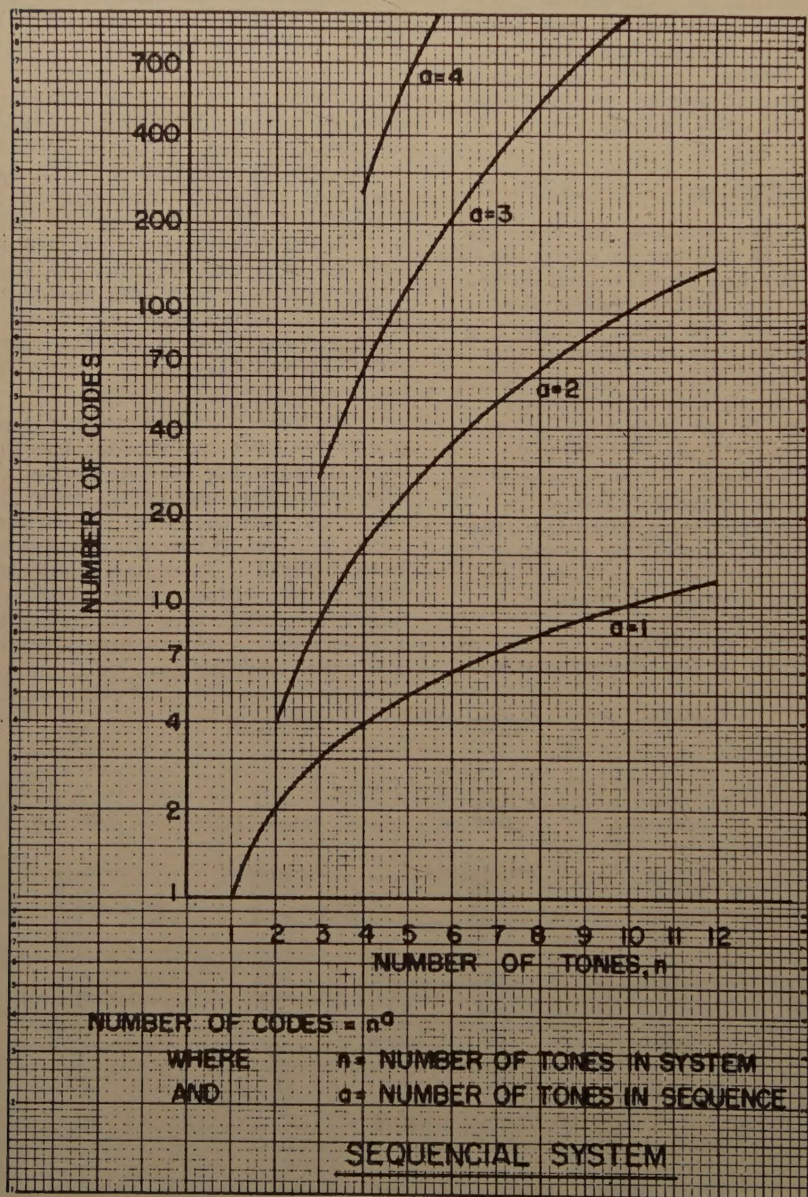

Fig. 3

The master controller has a program device that represents one week's time. For instance, at 8:00 A.M. Monday, the program timer automatically closes a contact that applies 115 V 60 c.p.s. on a wire connecting to all the secondary controllers. This voltage picks up appropriate relays that puts all controllers on Dial 1. The master is set up in advance, and by putting voltages on the interconnecting wires, tells the secondary controller what mode of operation is required. The master can also tell the secondary to FLASH, turn all Red for Fire Lane, or to SHUT DOWN.

A signal, consisting of the momentary removal of the voltage on the appropriate offset wire, is sent from the master once for each cycle of the timing unit. It keeps all the signals synchronized and in proper relation to each other.

Thus the interconnecting cable is used to control the mode of operation of each traffic signal and to keep them all synchronized.

VHF radio has entered the traffic control field by replacing the necessity of the interconnecting cable. All control functions are accomplished by the use of audio tone signals modulating the VHF carrier. The equivalent system shown in Figure 1 is replaced by that in Figure 2. The significance of this simple replacement may not be too obvious, but some of the advantages are:

1. Usually considerably lower initial system cost.
2. Greater system flexibility.
3. Ease of system expansion.
4. Centralized control of all systems within a community from a single location.

Tone Signalling System

Discussions with traffic control engineers has led to a basic system which contains ten functions; three dials, three offsets and two ON-OFF controls. More functions may easily be added if necessary. The coding system which incorporates a maximum of performance within economic limitations was selected on the basis of the following curves. Figure 3 relates the number of functions to the number of tones in sequence. It is evident that one good possibility is a two-tone sequential code requiring four tones total. However, sequential schemes usually require one tone receiver per code as illustrated in Figure 4. A system consisting of single-tone receivers, one for each tone in the system, is the most economical with respect to the tone receivers only. Complexities in the tone output switching arrangements usually make this form of coding less attractive.

Figure 5 relates the number of functions to the number of tones in a simultaneous tone system. Five tones satisfy the system requirements utilizing five tone receivers at each intersection. A simplified system of this type is shown in Figure 6.

The operation of any two tone receivers will energize an auxiliary relay as shown in Figure 7. This relay will supply power to the normal cable input requirement of a standard intersection secondary controller.

The tone receiver is an interesting device in itself, particularly with respect to its response characteristic as shown in Figure 8. In order to operate the end device, a relay, the input signal must fall within the closed loop of frequency vs amplitude. Note the roof on the characteristic. Strong amplitude signals are thus ineffective in causing unwanted operation. Remembering that two such signals must exist in the simultaneous tone code before an operation can occur to change the traffic pattern, it is quite evident that this system is relatively immune to false operations.

The principle of the tone receivers is shown in Figure 9 where amplifiers A_1 and A_2 are for-

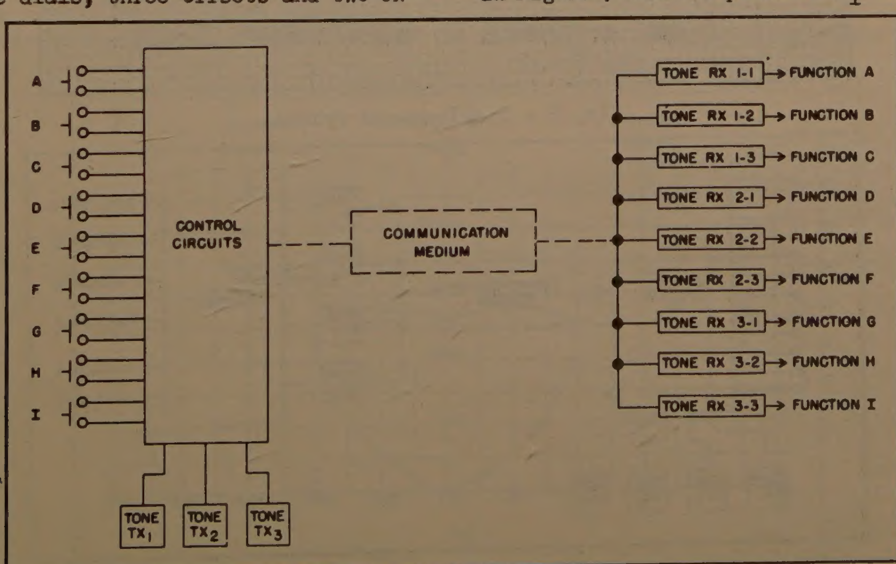

Fig. 4 - Two-tone sequential remote control system.

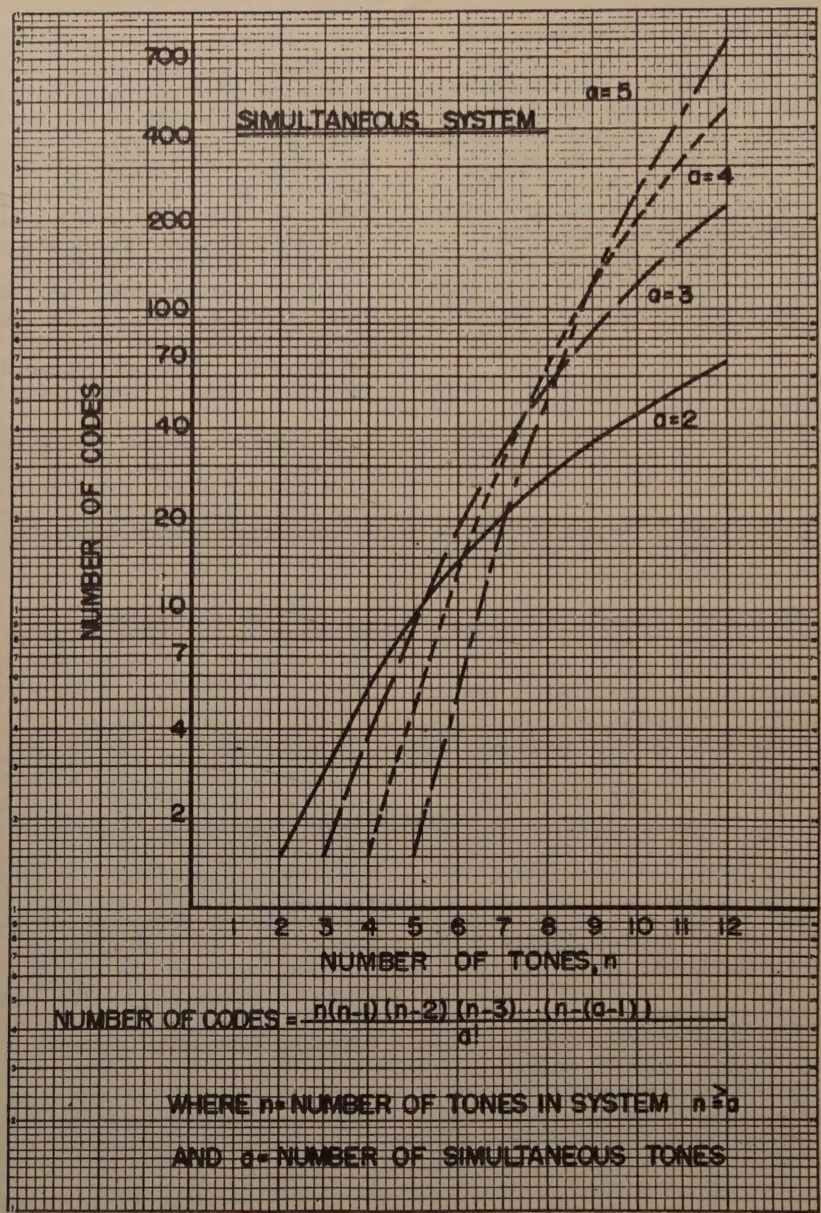

Fig. 5 - Simultaneous system.

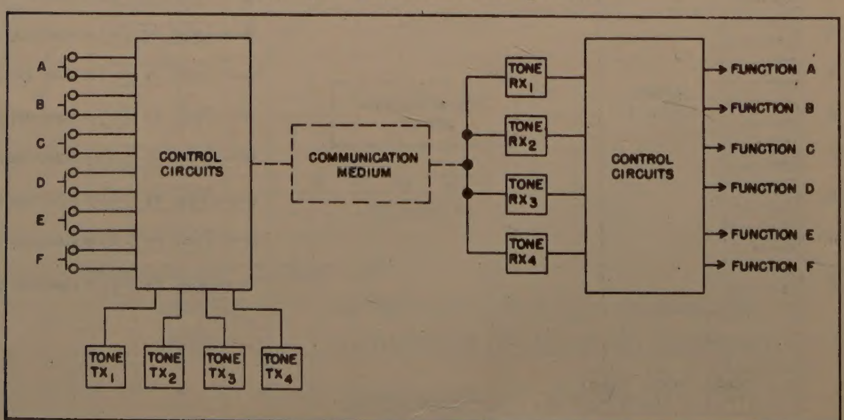

Fig. 6 - Two-tone simultaneous remote control system.

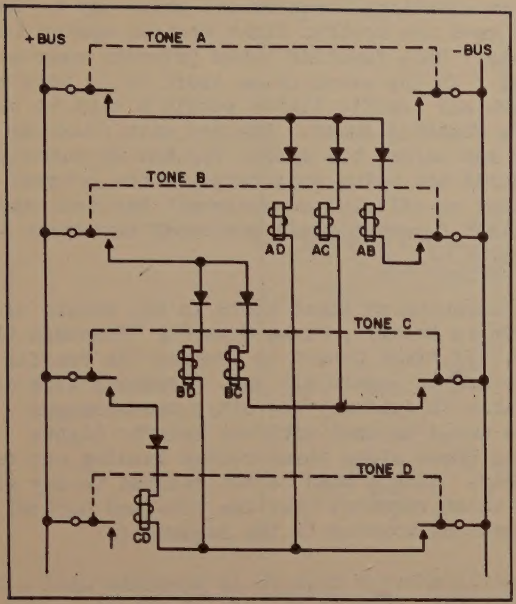

Fig. 7 - Auxiliary relay.

ward amplifiers whose output is selective as governed by the feedback Twin "T" network. The input of amplifier A_3 is taken from a point which has an inverse frequency characteristic. Connecting the rectified outputs of these forward and differential amplifiers gives the response as shown in Figure 8.

Secondary Tone Translator

The complete assembly of the VHF receiver, tone receivers, auxiliary relays and power supply is known as a Secondary Tone Translator. Figure 10 shows a photograph of a typical intersection assembly, the lower cabinet is a standard local controller as furnished by the manufacturers of the traffic light equipment. The upper cabinet contains, reading from the top down, a standard VHF mobile receiver, power supply, relay panel and tone receivers.

Each Secondary Tone Translator need not necessarily respond to all the signals sent out from the base station; it may respond only to certain portions. For example, a long avenue leading from the fringes of a city through to the downtown section may require the section on the edge of town to be on FLASH after an evening hour, say 10:00 p.m., and remain on FLASH until 6:00 a.m. In such a case only the intersections desired would be equipped and respond to the FLASH signal. Other intersections may be shut down completely at night time with respect to the traffic lights, such as large factory exits, requiring normal operation only a few hours during the day and a FLASH during the actual factory working hours. Other examples may be easily visualized which all add up to improved traffic conditions which are possible with a flexible system at a reasonable cost made possible through the medium of VHF radio control.

Master Tone Translator

The control equipment required to accept and store desired traffic patterns for a complete city for the period of a week's time, generate and transmit the tone codes corresponding to the desired traffic patterns and prevent itself from becoming confused under all possible conditions is known as the Master Tone Translator. Depending upon the number and type of commands which it must originate, this terminal equipment may grow to become relatively complex. For discussion purposes, we shall refer to a family of traffic lights which have the same dial and offset patterns as a Group. Within a Group there may be a partial breakup of FLASH, SHUT DOWN, etc., as discussed above, but the criteria are common dials and offsets, when used.

A city will most likely have more than one Group. To illustrate try to imagine that Figure 11 is a map of a city. Each number represents a traffic Group, having different traffic conditions.

1. Downtown area requiring a maximum of flexibility.

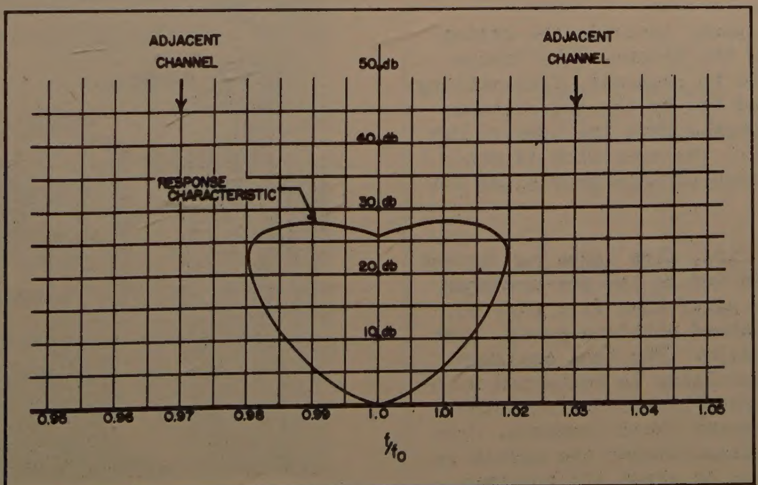

Fig. 8 - Tone receiver response characteristic.

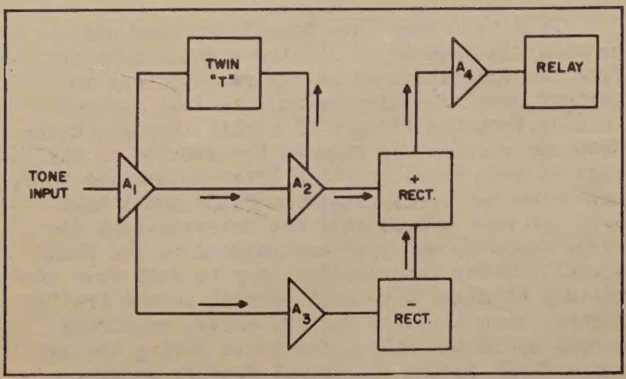

Fig. 9 - Tone receiver.

2. A park area, busy on weekends and holidays, or after working hours.
3. A thru-highway carrying traffic on a 24-hour basis.
4. Arteries leading to and from the industrial area carrying peak loads for short periods of time in the morning and evening.
5. Main arteries to the shopping area. Morning and evening peak loads plus shopping hours on certain evenings and weekends.
6. Neutral areas.

The objective is to develop a Master Tone Translator capable of handling this situation and also the many other cities, large and small, which may desire radio coordinated traffic light control systems. Flexibility must be included for conditions change rapidly within a community, new areas build up, new manufacturing plants spring up almost daily complicating the traffic situation.

Figure 12 describes in block form a method of approach to the Master Tone Translator. Each Group mounts in a cabinet and contains the equipment peculiar to that group under the command of a Sequencer. As conditions within the Group change, that group master is adjusted to comply with the desires of the traffic engineer. If more Groups need to be added, they take their place within the system under the wing of the Sequencer.

The Sequencer equipment controls the system through its commands to the Groups. The Groups are commanded to operate in sequence, transmitting the tone codes as called for by the information stored within each depending upon the time of day and the day of the week. The operation is completely automatic but does contain provisions for manual over-ride.

In the event of a fire, fire lanes can be set up which turn all lights Red on the pre-arranged street or streets for a particular fire station. A Fire Lane may be contained within a group, part of a group, or cross groups. The tone equipment and controls for the fire lanes is contained within the Sequencer. The Fire Lane function takes priority over the Groups and their commands. Upon completion of the Fire Lane command the system restores to normal and goes on about its business with the Groups.

An additional requirement which may be imposed upon the traffic light control system is Defense. This function takes priority over all others. In the event of an Alert it is possible to turn all traffic lights within a city to Red plus a Flashing Amber. The Red with Flashing Amber may become the symbol for the CD commands. Standards are being considered at the present time but no official announcement has been made. The Alert function would obviously encompass all Groups.

Following an Alert there is the choice of "Return to Normal", "Take Cover" or "Evacuate the City". If "Take Cover" is ordered the traffic lights are to remain all Red. Assuming time is available to evacuate the city, pre-arranged routes would be used with the traffic lights showing Green along these routes leading out of the city. Such a plan is not related to any given group which requires that the tone and control equipment be mounted in the Sequencer.

Still another feature is possible with a VHF radio system. During periods of extreme emergency, such as a CD Alert, the radio channel can be used to direct the people on the streets through voice communications.

Public address systems can be turned on and voice messages given to the general public via the VHF traffic light radio controlled equipment. The PA amplifier mounts in the same cabinet which houses the VHF receiver and tone equipment.

The first radio coordinated traffic light control system was installed in Chicago in 1955. It is the equivalent of three Groups. Figure 13 shows the Master Tone Translator. The manual over-

Fig. 10 - Typical intersection assembly.

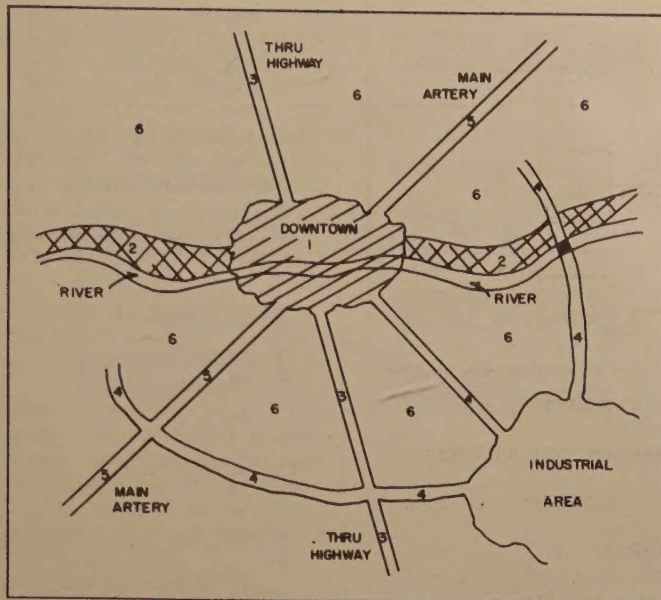

Fig. 11 - Typical City.

ride switch is on the front door, at the right. To the left of each switch are indicator lamps which show the traffic program existing at the time. The indicator lamps are particularly significant when on Automatic Program since no other simple method exists to show the operator the commands of the Master. In Figure 14 the left-hand cabinet houses the tone generator and a VHF remote control unit. The right-hand cabinet contains, from top to bottom, the master dial motors, automatic programing devices, recycle timers, control relays and power supply. A representation of the overall system is shown in Figure 15.

Beginning at the left is a Master Tone Translator, telephone line and VHF transmitter. At each receiving location is the Secondary Tone Translator, a secondary controller and the traffic lights.

A Look Into The Crystal Ball

A brief survey into the past of most control elements and systems reveals at least two things:

1. When first introduced a new function became possible which replaced a manual operation.

2. Improvements in the original device or system result in greater flexibility, broader application, increased precision and greater complexity.

Traffic lights have followed this pattern, replacing the traffic policeman, on busy intersections, and expanded through improvements of many types. The control of traffic lights with radio is simply another logical step in the evolution of more and better ways to do a job.

The systems described above fall into the general area of remote control or a one-way system. Greater accuracy can be achieved through the elimination of the need for the traffic engineer to estimate the probable traffic density and direction at each hour of the day by replacing the pre-arranged program with a dynamic one. Automatic traffic counters will analyze the traffic at critical locations throughout a city and relay information to a central computing machine which will automatically prepare data for transmission to the traffic light control system. Radio will be used on a two-way basis for this purpose, to prepare the traffic schedule before it gets there. Computors will prepare suggestions of alternate routes which are the least heavily loaded to common destination points through radio controlled illuminated signs.

In areas of extreme traffic density a modified version of the closed-loop television will monitor a small number of intersections, displaying each intersection on separate TV screens.

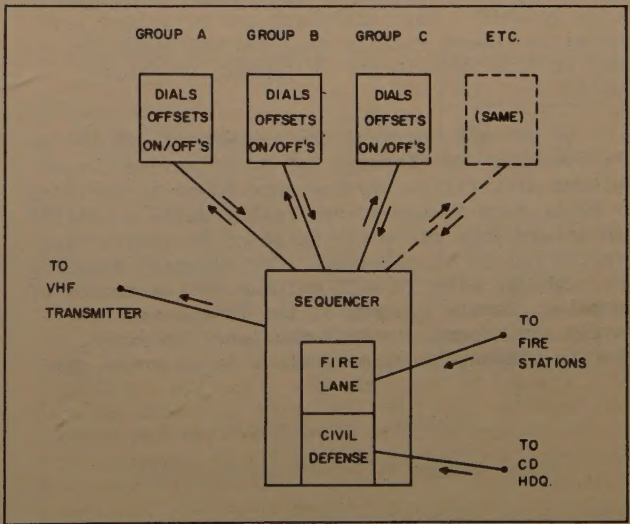

Fig. 12 - Master tone translator.

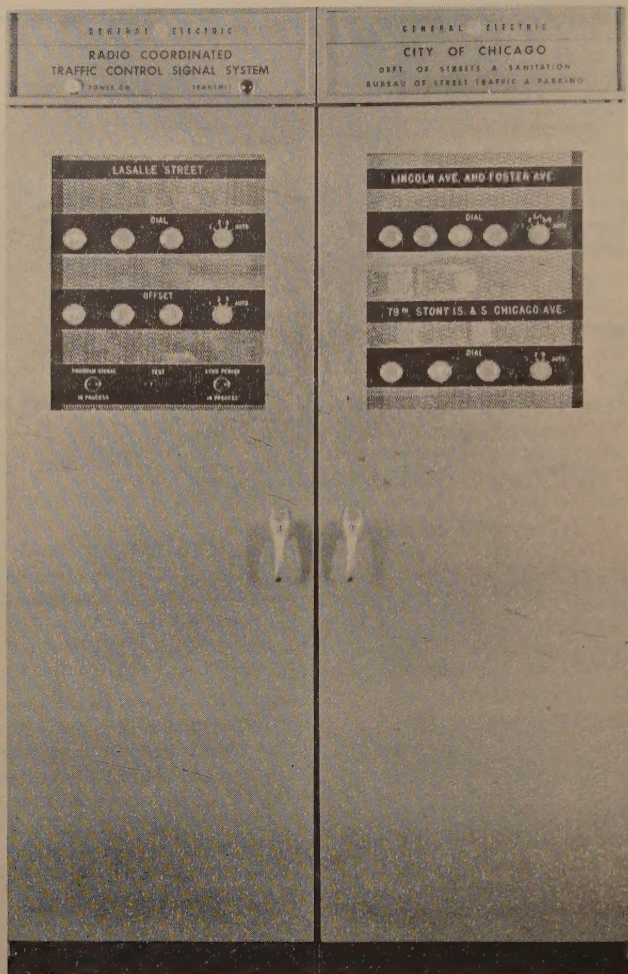

Fig. 13 - Master tone translator cabinet.

A single operator could then operate the traffic lights manually via a radio/tone system much as the traffic policeman now functions. A PA system for each intersection would permit commands such as, "Lady, get back on the curb until the light turns green!" More efficient use of police personnel is thus a reality with one man replacing four or five hard-to-get policemen for other duties.

We are all aware of the tremendous job which the freeways and thruways can do in moving large volumes of traffic. By the same token an accident or other form of tie-up can really cause a traffic jam unless some means can be found to divert the traffic before it piles up. Continuously scanning the highways with TV will quickly spot a source of trouble. Remote control of the TV cameras can easily aim, focus, control the lens' aperture, operate windshield wipers, etc., to zoom the picture in for closeups and make an almost instantaneous analysis possible by an operator. Then traffic patterns can quickly be set up and transmitted via VHF to divert traffic before it is too late. Fig. 16 illustrates some of the suggested signs that would be located over the roadways at intervals along the entire route.

The basic tool for accomplishing these results is the two-way mobile-type VHF radio communication equipment. To this versatile communication channel are addedtone and tone coding facilities. Microwave relaying, television, computors, and radar are used to extend the arm of control over larger areas to give precision on an automatic basis. More and more vehicles on essentially the same road surfaces demand greater emphasis on the positive control of their motion. We have the means and know-how at our disposal and are beginning to apply them.

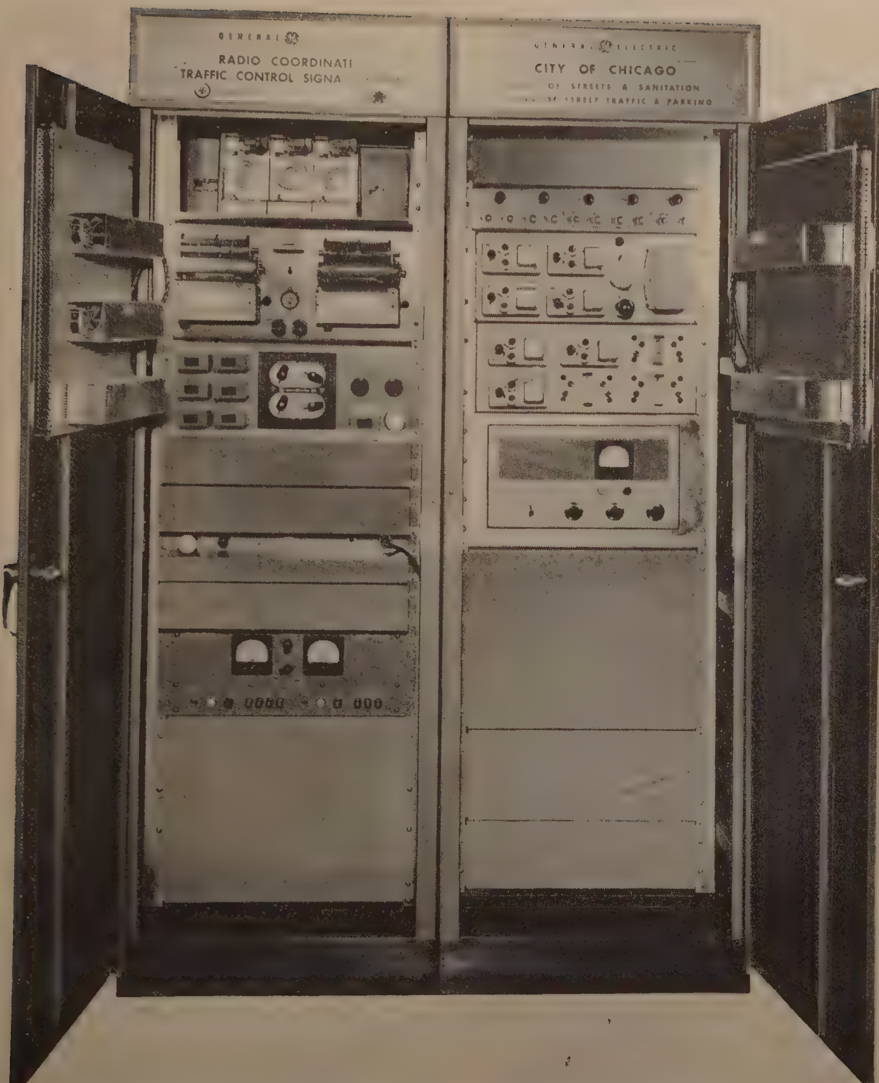

Fig. 14 - Equipment cabinets.

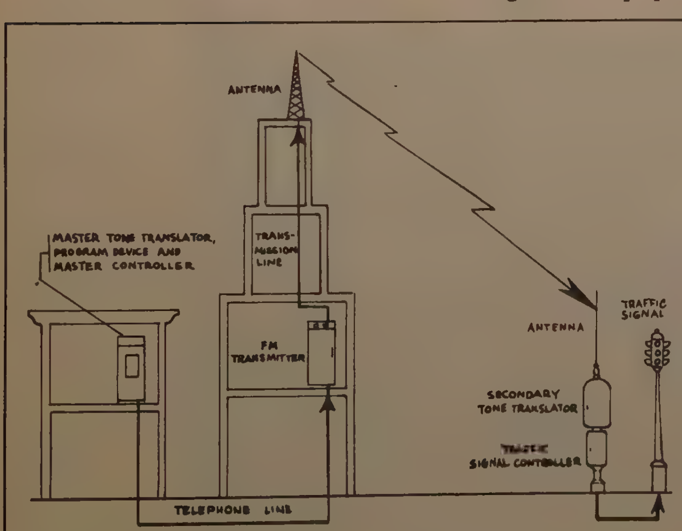

Fig. 15 - Typical installation.

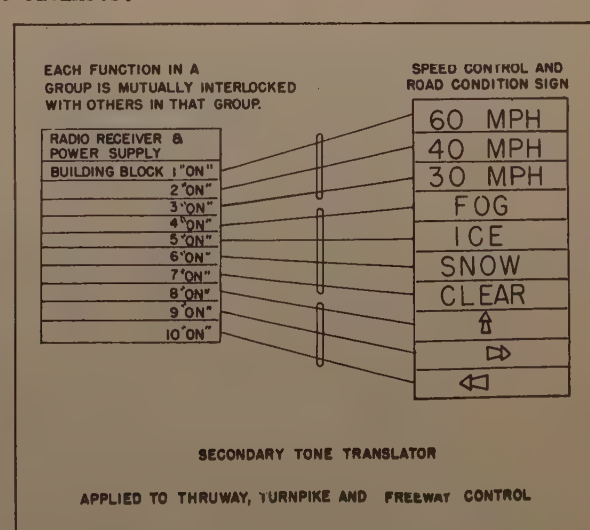

Fig. 16 - Roadway signs.

CRYSTAL OSCILLATORS IN COMMUNICATION RECEIVERS

Arthur G. Manke
Mobile Receiver Engineering
General Electric Company
Syracuse, N. Y.

Summary

The application of crystal oscillators to communications receivers is considered and the problems encountered are enumerated and separately analyzed. In regard to crystal oscillator operation, two typical circuits are cited for illustration and are analyzed in regard to the type of feedback used to produce oscillation. The analysis concludes that for maximum oscillator reliability in obtaining the inherent stability a crystal is capable of; regenerative feed-back which is present irrespective of the crystal impedance should be avoided and that these effects are largely determined by the type of crystal oscillator circuit used in a particular application. Over the temperature range normally encountered in communication receiver applications the reversals in the frequency vs. temperature characteristics for a typical close tolerance un-heated crystal is shown in Fig. #1. This data shows that for this type of crystal the total drift for temperature extremes is less rather than maximum due to the curvature of the frequency vs. temperature characteristic. Typical spurious responses of crystals normally used for oscillator purposes are also shown and the possibility of operation on spurious of the crystal is considered from a circuit viewpoint. Preferred methods for crystal oscillator injection and frequency trim are also discussed.

The crystal oscillator in the fixed tuned type of communications receiver has always been a very important portion of the receiver. Since receiver selectivity has in general been increased in recent years, the frequency determining or oscillator portion of the receiver must, therefore, also improve in reliability in order to keep up with the trend. This then poses the question of how can reliability be increased and to what features of the oscillator must we devote our attention in order to improve reliability. Is reliability increased or decreased with heated crystals or are there other factors which are of far greater importance than heated versus unheated crystals? The basic temperature drift of a crystal is a known factor and known factors are never a matter of much concern as they can be readily evaluated. It is, however, those things which involve a risk element or are subject to wide variation that are a matter of concern and, therefore, should be clarified and eliminated wherever possible.

A crystal heated or unheated always obeys the laws of nature and when properly applied and incorporated in a circuit where the crystal alone has control of the frequency of oscillation, the crystal is a very reliable device. Under these operating conditions it is therefore easy to determine if a crystal needs to be operated in an oven or if it has adequate stability for the particular assignment without the environment of a heated oven.

In the application of a crystal to the first or second oscillator of a communications receiver one is faced with four basic problems.

(1) To obtain the long time stability of oscillation which the crystal is inherently capable of delivering. That is the advertised stability of the crystal.

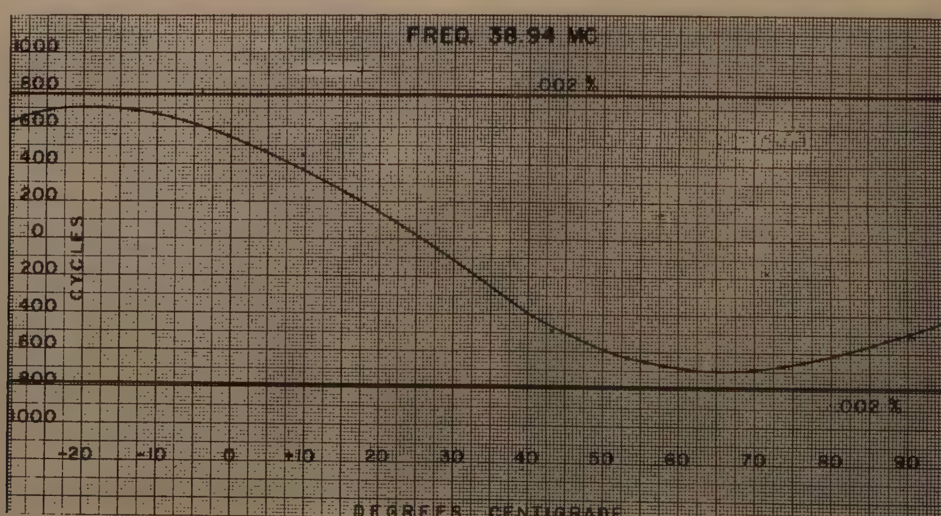

Fig. 1 - Crystal frequency variation vs. temperature.

(2) To provide adequate injection at a converter or to a multiplier over a given frequency range and not exceed the reliable activity at the highest operating temperature.

(3) To provide some rubbering or small frequency variation for trim purposes and not compromise the performance of the crystal in regard to stability.

(4) To prevent oscillation at the spurious responses of the crystal for all operating conditions.

These requirements are by no means simple or easily accomplished. Many people think that incorporation of a crystal imparts crystal stability to the oscillator. It would indeed be fortunate if this were always true.

Let us consider first #(1). What is meant by the advertised stability or the inherent stability which a crystal is capable of. It is a normal habit in the industry to measure or rate a crystal by subjecting the crystal only to a temperature range such as -30° to +100°C while the crystal is operating at a specified activity. The circuit and oscillator tube are held at room temperature, and the temperature cycle is completed within approximately thirty minutes. Such a short time test setup is certainly quite correct for determining the inherent characteristics of the crystal as regards frequency of oscillation and temperature in the particular circuit. It is, however, another matter to put this crystal into a receiver and exactly duplicate this temperature versus frequency curve such as is shown in Figure #1 and also meet the conditions stated in (2), (3) and (4) on a long time stability basis.

Figure #1 is a typical temperature vs. frequency curve of a .002% crystal (operating at 38.94 Mc) taken in the usual manner where the temperature variation is applied to the crystal only. If an appropriate circuit is used and the components in the oscillator circuit are of the proper type, then it is possible to get the crystal to duplicate this curve over the temperature range when it is in the working circuit of the receiver and also to do this on the long time stability basis. To duplicate this curve under all of the receiver operating conditions and continue to do so for the life of the crystal is, of course, a criterion which must be accomplished if the full stability of the crystal is to be realized in the application of the crystal to the receiver. This is what I mean by accomplishing problem #(1). To do this when the entire oscillator, (tube and circuit components), are exposed to the temperature and time variation is not as easy as when the crystal only is exposed to the temperature range and on a short time basis. Both the circuit used for the oscillator, (the method of feedback), (the variation of the loading of the crystal by the tube) and the components of the oscillator circuit will determine if this is accomplished.

In looking at crystal oscillator circuits, we can classify them according to the type of feedback as this is an important factor in crystal oscillator performance. That is--does the circuit supply feedback regardless of the crystal impedance or activity—or is the feedback provided present only because of the impedance of the crystal? The next important question is: Does the feedback provided tend to make the oscillator run at the spurious responses of the crystal or is the feedback inherently of such a nature as to tend to make the oscillator run at the fundamental or lowest frequency response of the crystal? Also does the circuit have reactive or in particular inductive elements across the crystal or in series with the crystal, the self-resonances of which, together with those of the crystal, can have many combinations affecting the frequency of oscillation for varying supply voltages, varying tube characteristics, variation of circuit components with time, temperature, and the aging of the crystal. Certainly as we study crystal oscillator circuits with these type of questions in mind, many of the previously misunderstood things that have happened to crystal oscillators can be readily accounted for.

Let us take a look at some typical crystal oscillator circuits that have been used for many years and also at some of the more recently used circuits. Some of these circuits have acquired names due to patent dockets and others have not. If studied with respect to feedback, we can classify any of the circuits quite readily. Typical crystal oscillator circuits are the Butler, Miller, and Pierce.

We will first look at the Miller circuit Figure #2 with respect to type of feedback used to produce oscillation.

Here the crystal is between the grid and ground and, therefore the crystal must operate at essentially parallel resonance as oscillation could not be explained under any other conditions. The capacity from grid to ground if a trimmer is not used will be the tube capacity plus the crystal mounting capacity. In this case it is important to note that the crystal determines the

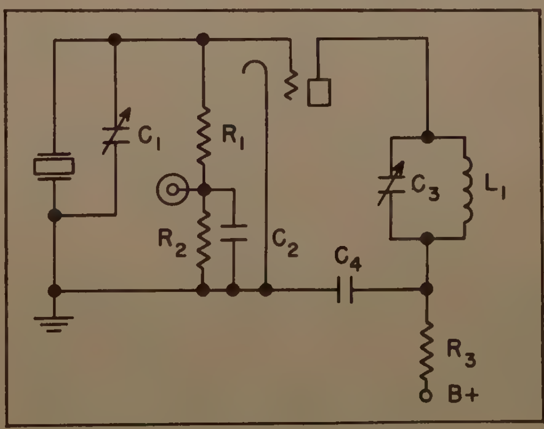

Fig. 2 - Miller oscillator.

impedance from grid to ground, therefore, oscillations are entirely controlled by the crystal. The grid circuit will also have impedance at the spurious responses of the crystal and this will be in proportion to the magnitude of the spurious responses. Let us look at the feedback of this circuit and determine how prone it is to oscillate irrespective of the crystal or with the crystal replaced by a capacitor of equal value. If we put a 15 MMF capacitor between grid and ground, what are the possibilities of self-oscillation of this circuit? In reality there are no possibilities or tendencies toward self-oscillation since a tube with a tuned circuit in only one of its three elements (the plate) and the other two elements grounded or connected to ground thru a resistor shunted by capacitor has never been known to have any tendency towards oscillation. We, therefore, see that this circuit has no feedback paths or oscillation tendency at or near the crystal frequency when the crystal is replaced by its equivalent capacity. (By equivalent capacity I mean the capacity between the plates of the crystal with the quartz as a dielectric.) Other obvious advantages in this circuit are that the crystal can have complete control of the frequency of oscillation since all the feedback to produce oscillation occurs due to the impedance of the crystal and the crystal is loosely coupled to the LC tank circuit. In other words the circuit does not have inherent regenerative feedback irrespective of crystal impedance and therefore the crystal can be the frequency determining element of the oscillator circuit. This circuit, is of the type which will allow the crystal to perform according to the thickness of the crystal blank, the angle to which the crystal is cut, and the loading. The loading is determined by the thickness of the plating and electrical loading or capacity across the crystal. Let us look into the electrical loading a little further, as so far, the circuit seems to be perfect and such things are very rare in nature. Part of the electrical loading is due to the tube, therefore, we should experience some variation in the loading as tubes are changed or as a tube ages and, there should be some change in frequency. A trial to see what happens after selecting tubes which vary widely in mutual conductance shows that for an oscillator operating at 15.0 M.C., changing tubes which vary two to one in mutual conductance, will change the frequency of oscillation by 35 cycles. The input capacity of the tubes were not identical and the capacity across the crystal due to mounting plus the trimmer was 9 M.M.F. From this it is obvious that the aging of the tube will affect the frequency, however, for use in communication receivers such a change is entirely tolerable for this application.

This circuit is also unusually free from operation on spurious responses of the crystal. The reason for this can be seen by drawing a vector diagram of the plate and grid voltages which exist for oscillation on the fundamental response of the crystal. Since spurious response are always higher in frequency than the fundamental response, the phase relations in the plate and grid circuits are such that more energy is transferred from the plate circuit to the grid circuit for the lower frequency which is the fundamental response instead of a spurious. This is also the case for a mode crystal. In testing this circuit for operation on spurious responses of the crystal at 34.0 M.C., it was observed that although a spurious response was 92% of the fundamental and only 80 Kc higher in frequency out of 34.0 M.C., it was impossible to get this circuit to oscillate on this spurious response or any of the other spurious responses of this crystal. The plate tank of the oscillator was tuned higher in frequency so as to reduce the grid current 25% below the maximum value.

Let us now consider the circuit of Figure #3 which has been used extensively both with fundamental and mode crystals. In some applications

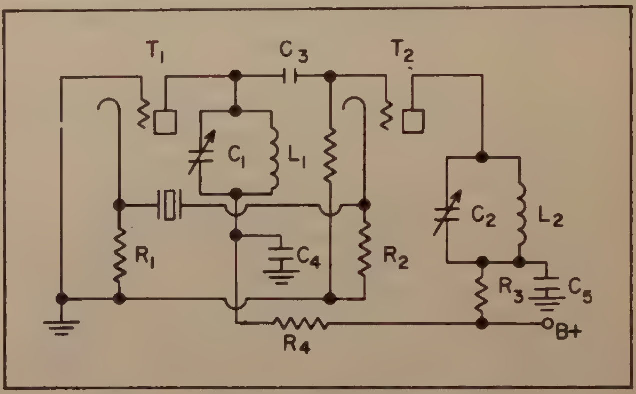

Fig. 3 - Crystal oscillator circuit.

this type of circuit was used to provide rubbering by tuning L_1 C_1 and in other cases rubbering or frequency trim was provided by varying L_1 C_1 and a reactance in series with or across the crystal. Tank circuit L_2 C_2 is usually tuned to the second or third harmonic of the crystal be the crystal a fundamental or a mode as the L_2 C_2 tank is most frequently used as a multiplier for the crystal. In the case where no frequency trim is provided, the plate tank, L_1 C_1 is usually tuned higher in frequency than the tuning which gives maximum crystal activity. As we analyze the feedback paths in this oscillator circuit, it is immediately evident that the crystal must operate at series resonance, in order to provide feedback for oscillation. Under this condition there is a feedback path between the two cathodes depending upon the series resistance of the crystal and the capacity of the crystal. For mode crystals the series resistance might be 25-30 ohms and the crystal capacity is frequently 15 MMF including mounting and lead capacity. When used in the 30-40 Mc range, the crystal capacity alone will provide a coupling of 300 ohms between cathodes. If the cathode resistor of T_1 is 330 or 470 ohms, then there is a 50% feedback (from T_2 to T_1) of the energy present in the cathode of T_2 in the frequency region where L_1 C_1 is tuned. Tank circuit L_1 C_1 is tuned relatively close to the frequency of the crystal. It is important to note that this feedback path exists regardless of the crystal impedance and is not directly controlled

by the crystal. If the series resistance of the crystal is 30 ohms, then the feedback due to the crystal activity would be ten times that of the feedback path cited due to the capacity of the crystal. At the frequency of the crystal there is normally considerable limiting present both in T_1 and T_2, however, this is not the case for the feedback which takes place due to the crystal capacity as its amplitude is much too small. From this analysis it is evident that this crystal oscillator circuit has some rather fundamental differences when compared to the crystal oscillator circuit of Figure #2. This can be further verified by replacing the crystal with an equivalent capacitor and making observations on oscillation, and tendencies toward sustained self-oscillation by a slight increase in crystal capacity. It is also important to note that this circuit is in effect similar to any triode crystal oscillator circuit which has inductive elements in any two of the three elements of the tube. Regardless of where or how the crystal is incorporated in such a circuit the tendencies toward self-oscillation are inherently built into the circuit and with this condition present the tendencies toward self-oscillation will extract their toll from the inherent stability of the crystal. In this circuit note that T_1 has L_1 C_1 in the plate and L_2 C_2 essentially in the cathode due to the coupling between the two cathodes. Any circuit which has appreciable feedback not controlled by the crystal reactance will, of course, be prone to operate at one of the crystal spurious responses in a random manner and especially so if the feedback path is more effective for frequencies higher than the fundamental of the crystal, as is the case cited above.

Also it must be remembered that where the crystal does not have complete control of feedback, the oscillator is continually under the influence of the other feedback and this feedback is not at the crystal frequency, consequently the long time stability of such an oscillator is not equal to one having the characteristics of the oscillator shown in Figure #2.

The crystal oscillator circuit of Fig. #3 has a number of advantages over the circuit of Fig. #2 in regard to crystal yield. That is for high frequency (30-50 Mc) 3rd mode crystals there will be very few rejects for activity out of a thousand crystals. Out of the same batch of crystals there is likely to be at least 5 to 10% rejects for activity when these same crystals are tested in the circuit of Fig. #2. Also it is possible to operate 5th and 7th mode crystals (85-100 Mc) in the circuit of Fig. #3 whereas mode crystals at these frequencies are extremely difficult to produce for operation in the Miller circuit. Another feature of the Figure #3 circuit is that the crystal can quite easily be "rubbered" or trimmed. These advantages (rubbering and yield) are, however, in direct proportion to the stability the circuit is adjusted to; and this is accomplished by proportioning the elements of the circuit such as R_1 R_2 R_3 and R_4, etc.

I hope the above explanations will serve to illustrate the circuit features of these two oscillators and from comparisons like these other oscillator circuits can be analyzed in regard to their desirability as crystal oscillator circuits which in their application are likely to yield the inherent stability of a crystal. This is, of course, a number one consideration when deciding whether or not a crystal can accomplish a given assignment with or without the assistance of the heated oven and whether or not automatic frequency control is required.

While we are on the subject of whether or not a given crystal can fulfill a given assignment let us take another look at Figure #1. This crystal was ground to meet a temperature coefficient of .002% over the range -30° to +90°C. Any crystal which is ground to perform to a coefficient of this order must have a curve shape of this type. That is it has these reversals and these reversals are determined by the angle to which the crystal was ground. Therefore, once a crystal is ground it will not and can not change its stability over the years providing it is incorporated in a circuit that does not interfere with the crystal; that is a non-regenerative circuit when the crystal is replaced with its equivalent capacity or a capacity appreciably larger than the crystal capacity.

It is interesting to observe the drift encountered with a crystal of this type in the various communication bands. This crystal is a mode crystal operating at 38.940 Mc and will, therefore, serve as a first oscillator without any multiplication in the 25-54 Mc band. We will assume the receiver was set on frequency after warm-up and that the crystal temperature was up to 35°C. If the temperature rises some time later to 75°C, the oscillator frequency will change by 370 cycles and should the temperature rise to 90°C the frequency shift will be 220 cycles. Should the crystal temperature go down to zero degrees C, the drift of the crystal would be 790 cycles. These are typical conditions for a mobile receiver in the 25-50 Mc range, and are drifts which would be of no concern as far as their effect on operation are concerned. For the 144 to 174 Mc range the crystal frequency at 165 Mc operation would be multiplied by four for operation in the higher frequency portion of this band. This would produce a drift of 1480 cycles for the 75°C crystal operation and 880 cycles for the 90°C crystal operation. These drifts are still small enough to have a negligible effect in practical operation where the system deviation is held to proper values. For zero centigrade condition the drift would be 3160 cycles. A measurement of signal-to-noise ratio of the receiver for this condition shows a degradation of one db in signal-to-noise ratio at standard sensitivity. This is not enough to be noticeable except by instantaneous comparison. Therefore an unheated crystal of this type would be satisfactory in both of these bands. In the 450-470 Mc range these crystal drifts would have to be multiplied by 2.5 as compared to the 144-174 Mc band. In this case the drift would be 7.8 Kc for zero degree crystal operation which is enough crystal drift to warrant the use of automatic frequency control or the heated crystal.

Oscillator Injection Considerations

Another important factor which can affect the crystal reliability of the crystal oscillator is the method used to extract the useful energy from the crystal and also the amount of energy the crystal must supply. If a coupling condenser is tied directly to the crystal and also to another tuned circuit in the grid of a converter, this can easily lead to serious variation in crystal performance at some frequencies in the band. Where energy from the crystal oscillator must be introduced directly into a converter stage, it is desirable to couple the converter stage to the plate tank of the oscillator or to use common cathode coupling so as to obtain additional isolation between the crystal and the tuned circuits of the converter stage. Common cathode coupling by means of a resistor is particularly advantageous for obtaining uniform injection over a wide frequency range and also most advantageous in maintaining the proper value of injection over a wide range of supply voltage. The same applies to injection into a multiplier stage where it is also important to obtain as much isolation as possible between the crystal and the tuned circuits of the multiplier stage. Besides obtaining adequate isolation between the crystal and the tuned circuits of the converter or the multiplier is the matter of strength of oscillation or dissipation in the crystal blank. Every crystal blank has a very definite value of dissipation which must not be exceeded if the reliable performance of a crystal oscillator is to be realized. Here the oven is at a considerable disadvantage since if the oven is going to give the performance claimed for it, then the oven temperature must be set at the highest ambient which the interior of the oscillator compartment is subject to in the particular equipment. It is obvious that the dissipation problem within the crystal blank has been increased many fold. A plot of frequency versus dissipation of a considerable number of a particular crystal will readily show the reliable temperature limits of operation of each crystal. The variation between apparently identical crystals can be appreciable and must be taken into consideration in the selection of a reliable activity level for each crystal application.

Crystal Rubbering or Trim Considerations

We will consider crystal trim or rubbering only in the case of the circuits shown in Figures #2 and #3. The very thought of being able to vary the oscillator frequency of a good crystal oscillator by means of varying circuit elements is at first hand alarming. The fact that this is accomplished without degrading a good crystal oscillator, that is making it regenerative, is certainly worthy of detailed consideration. One can easily visualize a crystal oscillator circuit which is appreciably regenerative being easily moved in its frequency of oscillation by varying some of the circuit constants, however, to do this and maintain an oscillator circuit where the crystal has complete control and the frequency of the oscillation is in reality controlled by the crystal blank and the thickness of plating on the blank is a condition which demands an explanation.

It is known that for piezoelectric devices as well as electro-mechanical devices the effect of electrical loading can be equivalent to mechanical loading. Certainly anything which has or produces the same effect as lighter or heavier plating on the crystal blank (loading) can safely be used to change the frequency of oscillation of the crystal, providing the loading is stable.

The mechanical loading effect can within certain limits be accomplished electrically by capacity loading. The method of connecting the condenser C_1 used for frequency trim is shown in Fig. #2. It is extremely fortunate in crystal operation, that the use of capacity in this manner will change the crystal frequency, as very stable capacitors have been developed and are readily available. This then gives us an ideal method of trim to enable varying the frequency of oscillation without compromising the stability of the crystal oscillator.

The use of capacity loading on crystals is, however, primarily limited to fundamental operation of the crystal. For mode operation of the crystal blank, the mounting capacity is very large thereby leaving a very limited range available for additional electrical loading or frequency trim. For this reason we do not see mode crystals which have frequency trim operating in the circuit of Figure #2. A method for trimming the frequency of mode crystals that is equal to the addition of capacity across the fundamental crystal has not been developed. This is not surprising as even with the crystal operating on its fundamental frequency the range of trim available by loading the crystal with capacity is very limited and the activity decreases rapidly with increasing capacity.

Spurious Responses of Oscillator Crystals

The fundamental response plus the spurious responses of two typical fundamental crystals and two mode crystals are shown in Figure #4. These responses are as seen on an oscilloscope and only the deflection above the horizontal line of the oscilloscope are shown. The vertical deflection in this case indicates series resonance of the crystal. It is interesting to observe that all the spurious responses are higher in frequency than the fundamental and also that the spurious nearest in frequency to the fundamental response is not necessarily the one having the greatest amplitude. The crystals of 4A and B operated in the 6 to 7 Mc region while the third mode crystals 4C and D operated in the 35 to 45 Mc region. The pattern of spurious responses of oscillator crystals may vary widely within the same production lot, and therefore the crystals are tested for spurious operation in a test circuit. The crystal blanks used in these crystals had all the standard precautions normally used in the manufacture of crystal blanks for oscillator crystals. Whether the pattern of spurious responses of a particular crystal will allow the operation on any of the spurious of a particular crystal depends almost entirely on the oscillator circuit. Any crystal circuit which has regenerative feed-

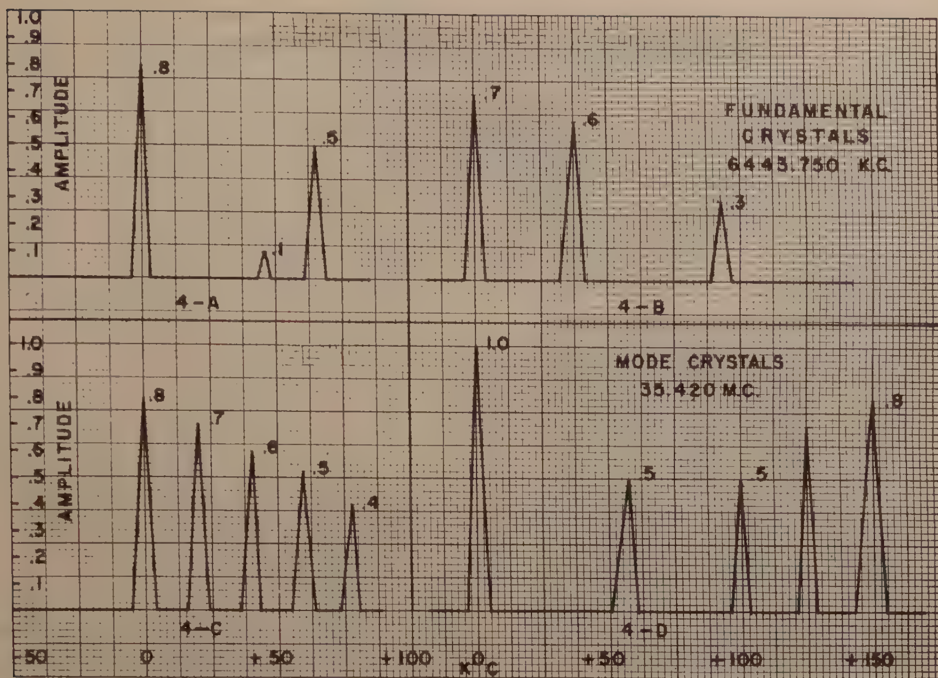

Fig. 4 - Crystal response curves.

back not dependent upon the crystal impedance, and in addition if the circuit elements are such as to provide feedback that favors oscillation at the higher frequency or the crystal spurious, will at times start and may continue to operate at one of the spurious responses. This shift in the crystal operation may appear to be entirely random, however, it can upon close study be explained in tube or crystal aging, relatively small shift in circuit component value or other environmental conditions. These type of effects when present account for many of the crystal replacements which have been made after a crystal has apparently performed satisfactorily for a considerable period of time. The circuit of Figure #2 is extremely free from this type of difficulty where as the circuit of Figure #3 and those having similar feedback are likely to encounter difficulties due to the spurious responses normally present in oscillator crystals. The capacity due to the tube and trimmer in the circuit of Figure #2 are directly across the crystal and therefore act as loading with more loading on the spurious as they are higher in frequency; and therefore make this circuit less likely to respond to the crystal spurious whereas capacity across the crystal in the circuit of Figure #3 would increase the feedback thereby producing the opposite effect.

In the summation of the above information, we see that in this matter of improving crystal oscillator reliability the important consideration is the type of circuit used for the crystal oscillator. The circuit should not have inherent regenerative feedback which is independent of the crystal reactance. The additional requirements usually imposed on the actual working circuit in the receiver can easily contribute to reducing reliability unless stringent precautions are observed in the method of obtaining injection voltages, the amplitude of oscillation, and especially the method of providing frequency trim of the crystal oscillator.

UHF COMMUNICATION SYSTEM INTERFERENCE REDUCTION THROUGH THE USE OF SELECTIVE FILTERS

M. W. Caquelin
Collins Radio Company
Cedar Rapids, Iowa

Summary

Modern trends in uhf communication systems indicate an ever increasing use of greater numbers of channels, higher transmitter powers, and decreased antenna spacing. This all adds up to an ever increasing number of systems interference problems. In most instances, a system can be rendered "interference free" by adding sufficient selectivity between the receiver or transmitter and its antenna. This added selectivity can be acquired by the use of a new low-loss tunable filter employing two high-Q, aperture coupled, resonant cavities in tandem. The physical construction of these equipments, as well as operating characteristics, will be discussed in this paper.

Introduction

Modern trends in uhf communications indicate an increasing use of greater numbers of channels with equipment and antenna massed in smaller areas. Transmitter power levels are higher. Antenna spacing is decreasing. Operational and financial considerations indicate a requirement for centralization of equipment. This all adds up to an ever increasing number of system interference problems. Field tests have shown that advanced interference rejection and elimination techniques must be employed if these newer systems are to be operational successes.

Much has been written on the possible types of interferences that may be found in such installations. Therefore, there is no need to discuss them in detail in this paper. As we all know, much can be done in the initial development of transmitters and receivers to reduce their susceptibility to these hazards but neither of these will be discussed. Beyond this, it can be shown that practically all types of interferences caused by off-channel signals as found in uhf communications systems can be reduced if not eliminated completely by adding sufficient selectivity between the receiver or transmitter and its antenna. (See figure 1.)

Added selectivity between the transmitter and its antenna attenuates undesired radiation and intermodulation products. Added selectivity between the antenna and its receiver reduces the level of undesired signals to the receiver.

This added selectivity can be obtained by the use of a new low-loss tunable filter employing two high-Q, aperture coupled, resonant cavities in tandem. Several

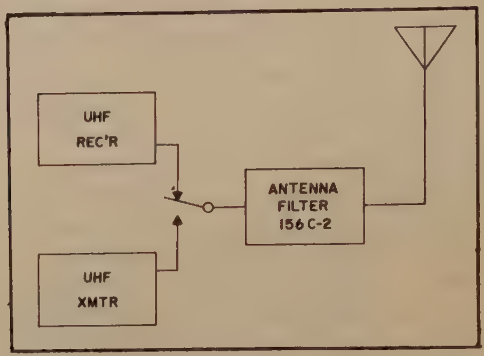

Fig. 1 - UFH communications system.

of these filters may be connected to one antenna through a suitable matching network. This combination is called a multicoupler.

These two types of selective devices will be discussed briefly before showing how they can be used in a communications system to reduce interaction and interference effects between the various transmitters or receivers in the system.

Antenna Coupler Description

First, the basic single channel antenna filter (156C-2) will be discussed. This unit is used to couple a receiver and/or a transmitter to one antenna. It is manually tuned and covers the frequency range from 225 to 400 mc. This filter is composed of two series connected cavities, each consisting of a closed coaxial line resonator, and with telescoping inner conductors.

This equipment may be mounted in a standard relay rack. The mechanism is mounted on a single, rigid plate with a single manual tuning control located on the front panel. A direct reading dial is provided to indicate the frequency to which the filter is tuned. A revolution counter dial also is provided so that an accurate logging may be made of preset frequencies if desired. Input and output connectors are located on the rear of the unit.

The mechanical construction of the cavity is quite simple, consisting of a simple cylindrical shell and a lead screw-operated internal plunger. (See figure 2.) Temperature compensation is accomplished by proper selection of materials and mechanical lengths in the cavity structure. The large size of the cavities and

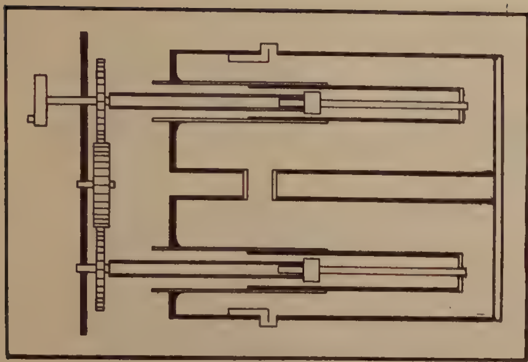

Fig. 2 - Antenna filter 156C-2

low-loss materials used in their construction result in an unloaded "Q" for each cavity ranging from approximately 7500 at 225 megacycles to 9000 at 400 megacycles. This is reduced to an operating value of about 1000 by the external load coupled into the cavities.

Each of the two cavities employed in the 156C-2 is a closed coaxial line resonator approximately one-quarter wavelength long at 220 megacycles. Tuning is accomplished by varying the length of the telescoping inner conductor by means of a lead screw mechanism. These two cavities, which are six inches in diameter, are connected in series to provide increased selectivity with little increase in insertion loss. Aperture coupling between cavities is used. The input and output circuits are loops located on the sides of the cavities and have one end grounded. The size and location of the aperture and the loops are important in controlling the selectivity and insertion loss of the unit across the assigned frequency range.

Specification Summary:

Weight and Dimensions:

Depth: 21-5/8 inches
Height: 7 inches

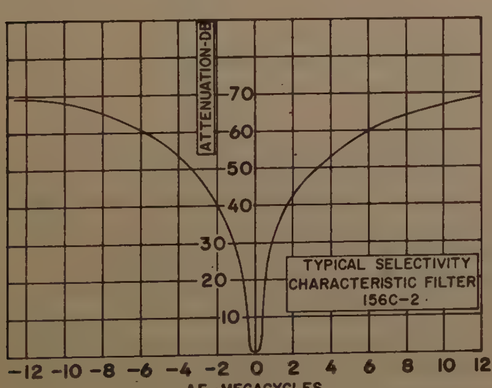

Fig. 3 - Typical selective characteristics, selective filter 156C-2

Width: 19 inches
Weight: 25 lb

Electrical Characteristics:

Frequency Range: 225 to 400 mc
Power Level: 0-200 watts
Insertion Loss: 1.5 db nominal
Input Impedance: 50 ohms
Output Impedance: 50 ohms

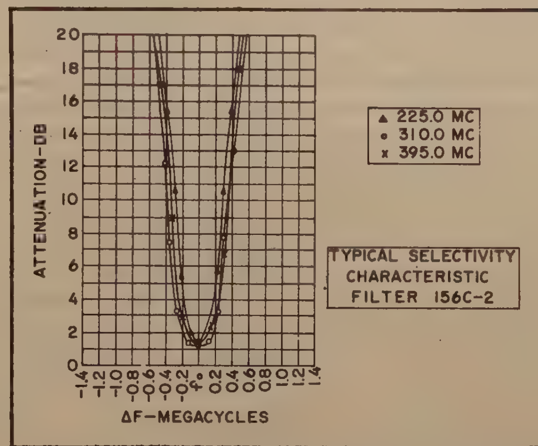

Fig. 4 - Band pass of selective filter 156C-2

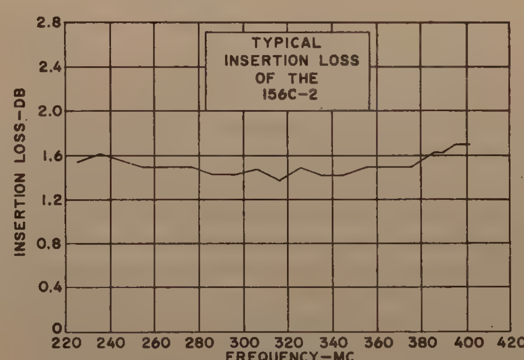

Fig. 5 - Typical insertion loss, selective filter 156C-2

Resettability: Less than 0.01-mc error

Resonant Selectivity:	Attenuation	Bandwidth
	20 db	±0.6 mc
	60 db	±7 mc

Operating Power Requirements: none

It should be noted that the tuning characteristics of the cavities are sufficiently similar to be tuned simultaneously from one panel knob. This unit could be redesigned to be tuned automatically if such a requirement arose.

In some locations it becomes necessary to couple several systems to one antenna. This tends to reduce the

isolation between equipments and increase the number of interference problems. One method of reducing this interaction would be to place a selective device or antenna filter in series with each of the receivers or transmitters and the common antenna.

An equipment which shall be referred to as antenna multicoupler 156B-4 has been developed to meet this requirement. This unit employs four sets of tandem cavities, each pair with a separate input but with their outputs combined through a special combining network. The use of such a multicoupler will allow the use of several uhf communication systems at one location and give a high degree of isolation between these equipments. The number of antennas required at an installation may be reduced by a factor of 4 to 1 through the use of such a multicoupler. (See figure 6.)

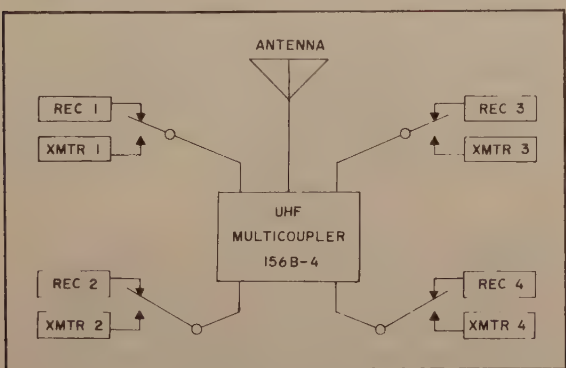

Fig. 6 - UFH communications system.

Antenna multicoupler 156B-4 is a device which can be used to couple a group of four transmitters, receivers, or combinations thereof to a common antenna without objectionable interaction between units. The operating frequencies of the group must be separated by a few channels, the exact number of channels depending on the characteristics of the auxiliary equipment. Within these limits, four inputs are available, each of which may be tuned to any frequency in the 225- to 400-mc range. The common terminal will terminate the equipment to match a nominal 50-ohm load.

Antenna multicoupler 156B-4 is superior to previous couplers in that two high "Q" cavities are used in series or tandem for each channel. (See figure 7.) This allows increased selectivity with little increase in insertion loss. The tandem cavities feature aperture coupling between cavities and input and output coupling loops on the side cavity walls.

This multichannel manually tuned multicoupler, which is characterized by simplicity of design and high quality in performance, is a reliable, functional field equipment of low production cost. It will solve many of the interaction and interference problems found in present day complex uhf communication systems.

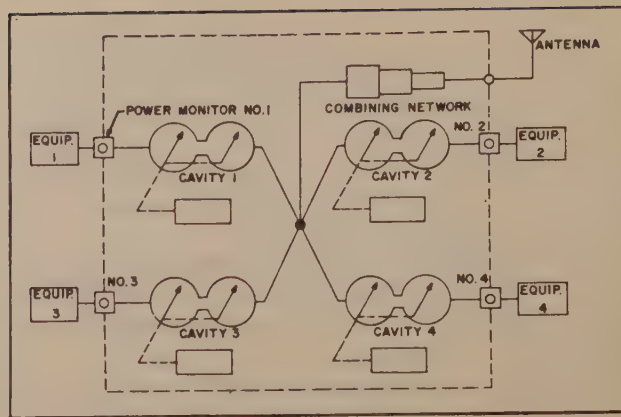

Fig. 7 - Block diagram, antenna coupler 156B-4

Summary

A. Mechanical

1. Size: 19" wide, 24-15/32" high, 17-3/4" deep behind rack mounting angles.
2. Type of Mounting: Standard 19" RMA panel rack or shockmounts.
3. Type of Coax Connectors: HN Antenna Output, N Antenna Input.
4. Coax Connector Location: Rear.
5. Type Tuning: Manual (one control and friction lock per channel.)
6. Number of Antennas Required: One (1).
7. Number of Equipments Coupled to Antenna: Four (4). Maximum.
8. Cavity Material: Silver plated aluminum.

B. Electrical

1. Frequency Range: 225 to 400 mc.
2. Input Impedance: 50 ohms.
3. Output Impedance: 50 ohms.
4. Off-Channel Rejection: 0.4 mc -- 12 db.
   1.5 mc -- 40 db.
5. Isolation Ratio: The isolation between two circuits of the coupler with frequency separation of 2 mc is approximately 55 db.
6. Insertion Loss Across the Band: 1.1 to 1.8 db.

Ordinarily the use of the single-channel filter-type unit is recommended to gain the added isolation between antennas. Even with the help of this added selectivity, some minimum frequency spacing must be maintained. Proper choosing of frequencies to minimize third and fifth order intermodulation products will allow closer frequency spacing. With proper equipment and frequency spacing, many receivers and transmitters can be operated at one location on relatively close channel frequency spacing.

The two most common types of interference radiated by transmitters operating in the 225- to 400-

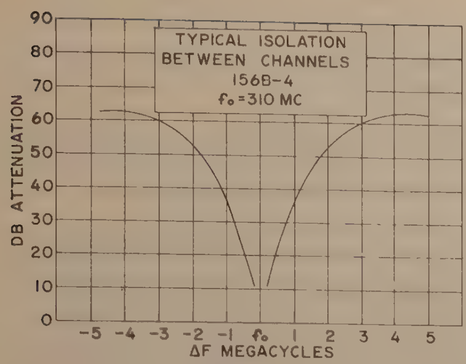

Fig. 8 - Typical isolation characteristic, antenna coupler 156B-4

mc frequency range are spurious signals from the transmitter's frequency generating system and intermodulation frequencies formed in the power amplifier of the transmitter. The second effect is the result of the output of one transmitter feeding into the power amplifier of a second transmitter and mixing to form intermodulation products. This effect can be reduced by the use of linear PA's but this practice is not in common use in this frequency range today.

Aside from receiving the above two types of extraneous signals which may fall on their resonant frequencies, receivers may respond to either their own spurious response frequencies or to crossmodulation and intermodulation signals from strong undesired signals. Desensitization may be a limiting factor but this effect is usually secondary to spurious responses, crossmodulation, and intermodulation.

It can readily be shown that all of these system interference problems can be reduced greatly, if not eliminated completely, by the use of the 156C-2 antenna

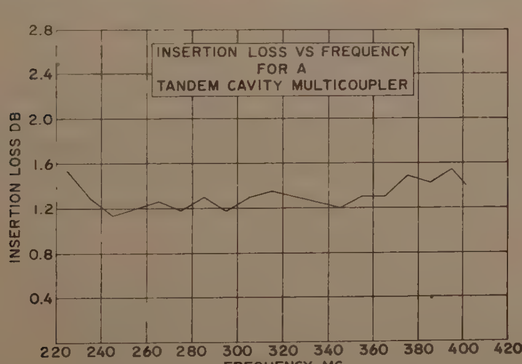

Fig. 9 - Insertion loss vs frequency, antenna coupler 156B-4

filter and 156B-4 antenna multicoupler. Actual field tests have been made to check the results of the theoretical calculations.

Consider that two of three dipole antennas are fed by 100-watt uhf transmitters and the third is connected to a receiver. (See figure 10.) The transmitting antennas are spaced 50 feet from the receiving antenna. Then the space attenuation at 310 mc would be

$$\frac{P_t}{P_r} = 70 \frac{D^2}{\lambda^2}$$

$$\frac{P_t}{P_r} = 70 \frac{(50)^2}{(3.18)^2} = 17,300 \text{ or } 42.4 \text{ db}$$

The output of a 100-watt transmitter is equivalent to +20 dbw.

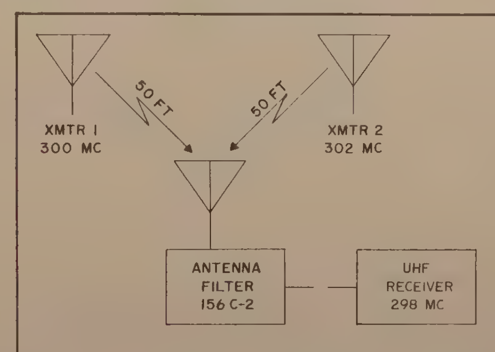

Fig. 10 - System using antenna filter 156C-2

Since the magnitude of third order interference generated in the receiver is usually greater than the interference generated in the transmitter, calculations given are for interference generated in the receiver. Consider 2-mc frequency spacing for the transmitters and that the receiver and antenna filter are tuned to the 2A-B (third order) frequency. (Xmtr power at Receiver) = (Xmtr Power Output) - (Space Attn) - (Filter Attn)

$$P_r - t_1 = 20 \text{ dbw} - 42.4 \text{ db} - 40 \text{ db}$$

$$P_r - t_1 = -62.4 \text{ dbw}$$

$$P_r - t_2 = 20 \text{ dbw} - 42.4 \text{ db} - 52 \text{ db}$$

$$P_r - t_2 = -74.4 \text{ dbw}$$

From the characteristics of a uhf receiver in common use today this would give a third order intermodulation figure of -140 dbw or 0.7 uv.

Without the cavities, $P_r - t_1 = -22.4$ db. This would give an intermodulation figure of -54 dbw or 14,000 uv. The system would be inoperable without the antenna filter.

Now consider the case where an antenna multicoupler is used. See figure 11.

Since the magnitude of third order interference generated in the receiver is greater than the interference generated in the transmitter, calculations given are for interference generated in the receiver. Consider 7.5-mc frequency spacing.

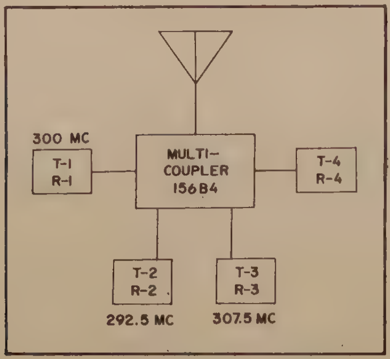

Fig. 11 - System employing antenna multicoupler 156B-4

Antenna coupler isolation T1 to R3 (7.5 mc) = 68
T1 power at R3 = +20 dbw - 68 db = -48 dbw
Antenna coupler isolation T2 to R3 (15 mc) = 80 db
T2 power at R3 = +20 dbw - 80 db = -60 dbw
Average transmitter power at R3 = -54 dbw
3rd order interference level at R3 = -142 dbw or 0.5 uv

Fig. 12 - Selective filter 156C-2

Without the multicouplers, the output powers of the two transmitters would have been directly across the receiver input connector.

In summary, it might be said that the antenna filters and multicouplers that have been discussed were designed to supplement the selectivity of the

Fig. 13 - UFH Tandem Antenna Coupler 156B-4

tuned circuits in receiver r-f stages and transmitter final output stages. This added selectivity is necessary only where there is a high density of equipment with close antenna spacing. The design effort has resulted in a simple, reliable piece of equipment suitable for these field applications and meeting their requirements. Without them, the channel spacing required in many systems for "interference-free" operation would be prohibitive.

COMMUNICATION WITH MOVING TRAINS IN TUNNELS

By Newton Monk and H. S. Winbigler
Bell Telephone Laboratories, Incorporated
New York, N.Y.

Synopsis

This paper describes tests conducted in the North River tunnel of the Pennsylvania Railroad to determine a practical means for communicating with moving locomotives and trains in tunnels. It is shown that frequencies between about 25 and 1500 megacycles per second are not suitable for such communication over any substantial distance when employing conventional radio techniques. Tests are described utilizing other means of transmission, including the use of a series of antennas bridged onto a transmission line extending through the tunnel, and a closely-spaced two-wire line without antennas acting as a radiating and pick-up device. It is concluded that satisfactory transmission in tunnels can be obtained for a distance up to approximately 6,000 feet using the frequencies and equipment ordinarily employed in railroad mobile systems and twin-lead cable such as RG-86/U suitably located within the tunnel.

Introduction

Very early in the application of radio to the nation's railroads it was found that, for the frequencies used, the radio signals did not penetrate into tunnels beyond a few hundred feet. Thus, communication with the trains when they are within tunnels of any substantial length is not possible with the existing radio systems. To determine a feasible method for obtaining communication with locomotives and cabooses when they are in tunnels, a number of tests were made by Bell Telephone Laboratories in cooperation with the Pennsylvania Railroad in the railroad's North River tunnel. This paper describes these tests and outlines an arrangement which is believed to be practicable for communicating with trains in tunnels.

As assigned by the Federal Communications Commission, frequencies in the range of 159 to 162 megacycles are used by the railroads in their road and yard radio installations. It is highly desirable that the same communication facilities be employed when the trains are within tunnels as are used at other times. For this reason most of the tests described in this paper were made at frequencies in the neighborhood of 150 megacycles. However, a few tests were made at higher and lower frequencies.

Description of Tunnel

The Pennsylvania Railroad's North River tunnel passes under the Hudson River between New York and New Jersey. It consists of two separate tubes, each of which carries a single track. One tube is known as the "north tube" and the other as the "south tube". Normally, trains leaving Pennsylvania Station in New York pass through the north tube, while incoming trains use the south tube. The tests were made in the north tube.

The tubes measure 13,393 feet from portal to portal. In addition to the entrances, there are two shafts at intermediate points through which access to the tunnel is possible and where base station equipment can be located. One of these is at 32nd Street and 11th Avenue, Manhattan, and the other is in Weehawken, New Jersey. A simplified diagram of the north tube, showing the location of these shafts and other pertinent information, is given in Figure 1.

The tubes are substantially straight throughout most of their length, with a

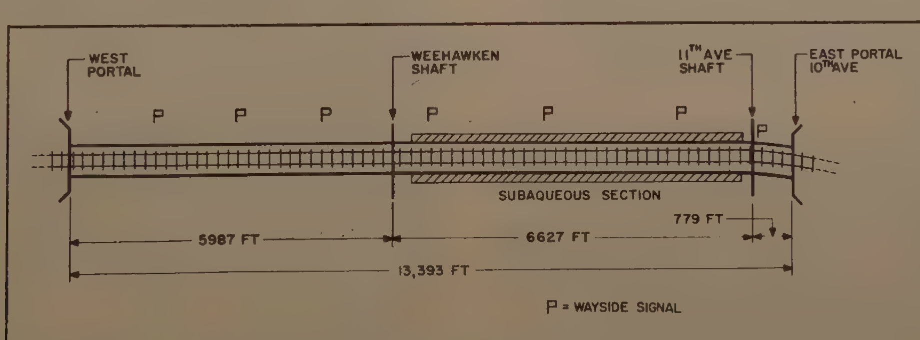

Fig. 1 - Simplified diagram of north tube.

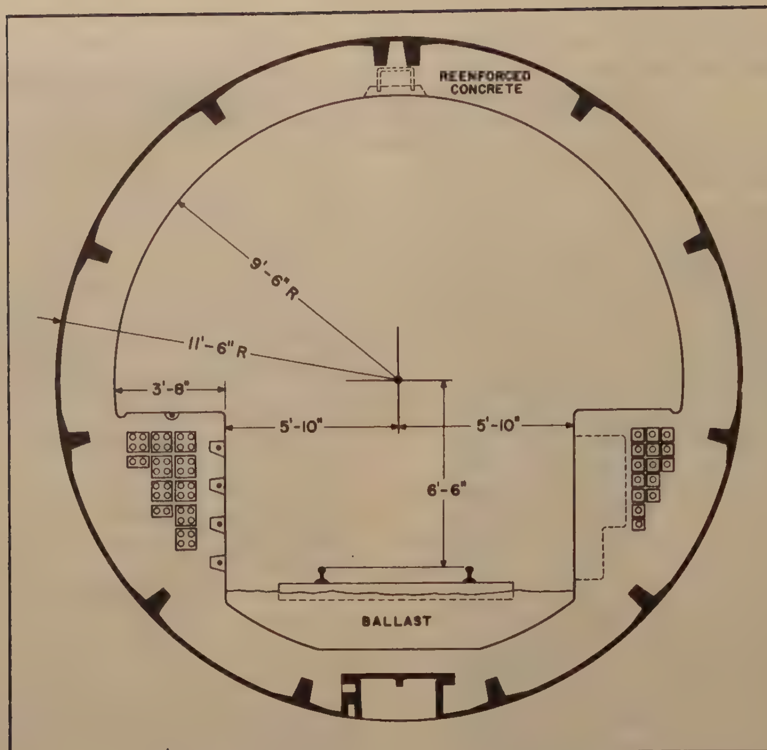

Fig. 2 - Cross-section of north tube.

two-degree curve close to the eastern end. Starting at the Manhattan portal there is a 1.92 per cent descending grade changing to a 0.53 per cent grade about 3,000 feet from the portal. This latter grade holds for about 2,000 feet under the river, from which point there is a 1.3 per cent rise in grade to the west portal.

Between the New York and New Jersey shafts the tubes are of typical under-water construction, being composed of a circular cast steel shell with a reinforced concrete lining. The nature of the tube construction over most of this length is indicated in Figure 2. It shows, in simplified form, the segmented cast steel ring construction of the shell, the reinforced concrete lining, and other features. West of the New Jersey shaft the reinforced concrete tubes have an interior configuration like that shown in Figure 2. East of the New York shaft the tubes are somewhat wider and higher internally.

Radio Propagation

Although it was already known that the loss at VHF radio frequencies was extremely high in tunnels, it was believed that knowledge of the approximate loss in the tunnel under test would provide a firm basis for further experimentation. Accordingly, radio propagation within the tunnel, in the 152-162 megacycle band, was first studied. A 30-watt radio transmitter and a companion receiver together with the necessary control and power equipment were set up in a small room at the foot of the 11th Avenue shaft. Figure 3 is a photograph of this station. The radio transmitter, control panel, and power panel are mounted in the larger rack, and the radio receiver in the smaller one. The radio equipment was connected through an adjustable attenuator, included on the control panel, and a suitable length of RG-8/U cable to a coaxial antenna located within the tunnel about as indicated in Figure 4.

The radio equipment was arranged to operate on a common carrier channel which is assigned for use by the New Jersey Bell Telephone Company in this area. This channel uses frequencies of 152.75 megacycles for transmission from the base station to the mobile units, and 158.01 megacycles for transmission in the reverse direction. By employing these frequencies, tests could be made with existing public passenger radiotelephone installations on a number of trains which pass through the tunnel daily. A mobile station operating on these frequencies, which was installed on one of the railroad's electric locomotives for radio survey purposes, also was available for the tests.

With the arrangements described, talking tests were conducted to and from

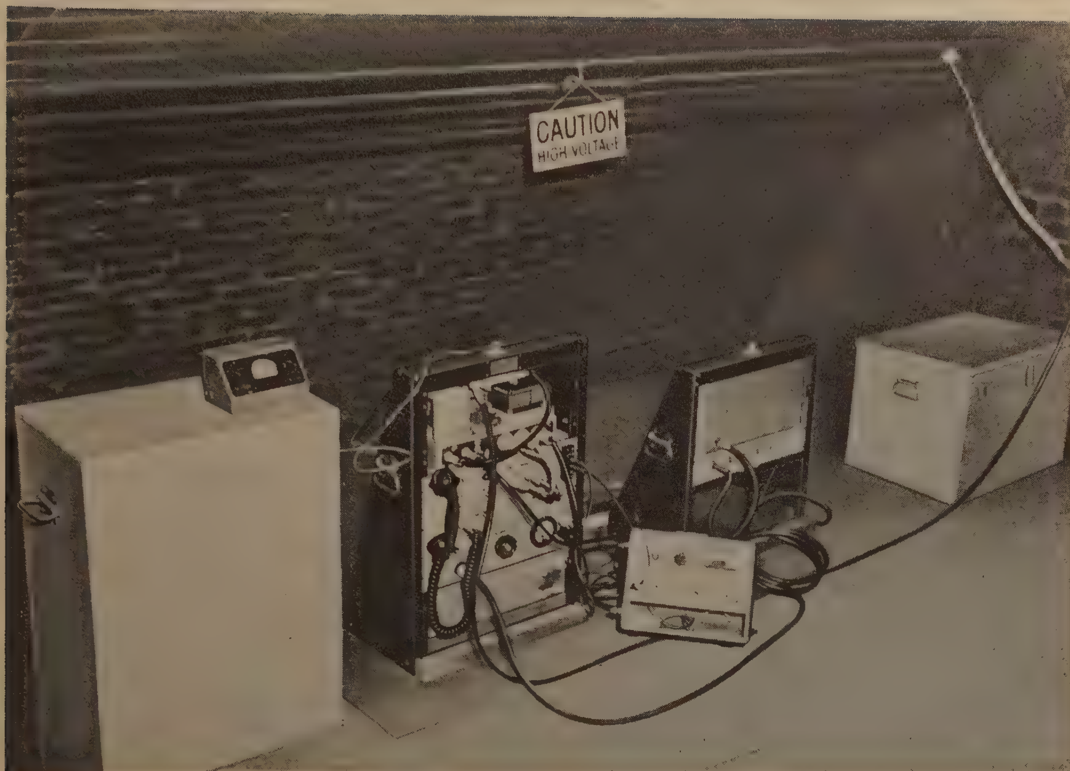

Fig. 3 - Base station equipment at the 11th Avenue shaft.

the trains with a variety of antenna types, heights, polarities, and orientations, and with several values of attenuation inserted between the base station and the antenna. Also, recordings were made of the signal strength received at the base station from the passenger train or the locomotive. By noting the instants at which the train station passed certain wayside signals during its passage through the tunnel, plotting a train progress curve, and coordinating this information with test times, the location of the train station at any time during the tests was quite accurately determined.

The results of the propagation tests for a representative antenna are summarized in Figure 5. This shows the distance from the base station for which reliable communication could be obtained plotted against the power output of the radio transmitter. Data for both directions of transmission are included. Unavoidable changes in day-to-day values of the mobile transmitter output and receiver sensitivity probably account for most of the observed scattering of the data. The straight line drawn through the test points indicates that the average attenuation of the radio waves at 152 megacycles over the path measured is in the order of 18 db per hundred feet. It should be noted that this attenuation is not that for an empty tunnel since, during the tests, the path between base and mobile station antennas was at least partially occupied by the train. For a 30-watt (+15 dbw) transmitter, this attenuation permits a range of only about 750 feet.

A recorded sample of the signal from the locomotive, as received at the base station, is shown in Figure 6. The

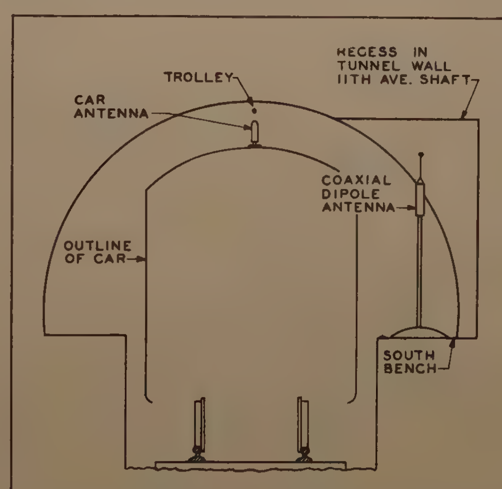

Fig. 4 - Base station antenna location and mounting.

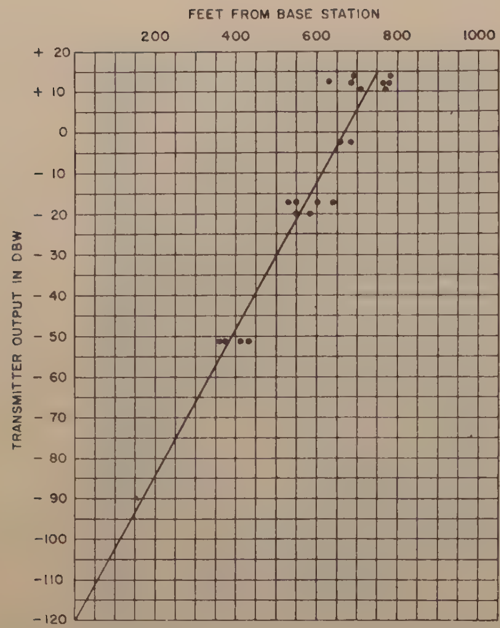

Fig. 5 - Radio coverage vs. transmitter output at 150 megacycles.

curve represents the build-up and decline of the received field strength as indicated by receiver first limiter current when the locomotive enters and leaves the coverage area. It will be noted that the received signal strength varies about as would be expected, and no substantial irregularities are evident.

In order to determine the possibilities of utilizing frequencies of the order of 40 or 450 megacycles some further data were obtained at these frequencies. In these cases talking and listening tests only were made. For the 40-megacycle tests, suitable base station equipment and trains equipped for public passenger service operating at approximately this frequency were used. For the 450-megacycle tests, a commercial TV converter was purchased, suitably modified, and installed on one of the 150-megacycle-equipped trains to convert the incoming signals from 450 megacycles to the carrier frequency of the 150-megacycle receiver. These tests indicated that the average radio attenuation over the test path at 40 megacycles was about 3.6 db per 100 feet and that at 450 megacycles approximately 12 db per 100 feet.

The above data together with the results of tunnel tests made by observers as gleaned from the literature* are plotted in Figure 7. The points on this curve are by no means accurate but are believed to indicate the order of magnitude of the loss in the radio path in a railroad tunnel when occupied by a train. It will be noted that the loss increases rapidly with frequency in the VHF range and decreases again as the frequency is increased. This suggests a change-over from free-space to waveguide transmission. Computing the critical cut-off frequency of a circular waveguide having the approximate dimensions of the tunnel under test, we find that the cut-off frequency varies somewhat with the mode of transmission but is in the order of 50 megacycles. However, if the dimensions of the waveguide are reduced to take account of the presence of the train within the tunnel and absorption affects, the cut-off frequency is substantially increased. Figure 7 suggests that this cut-off frequency is about 275 megacycles. The curve indicates also that 150 megacycles

*See Bibliography at the end of this paper.

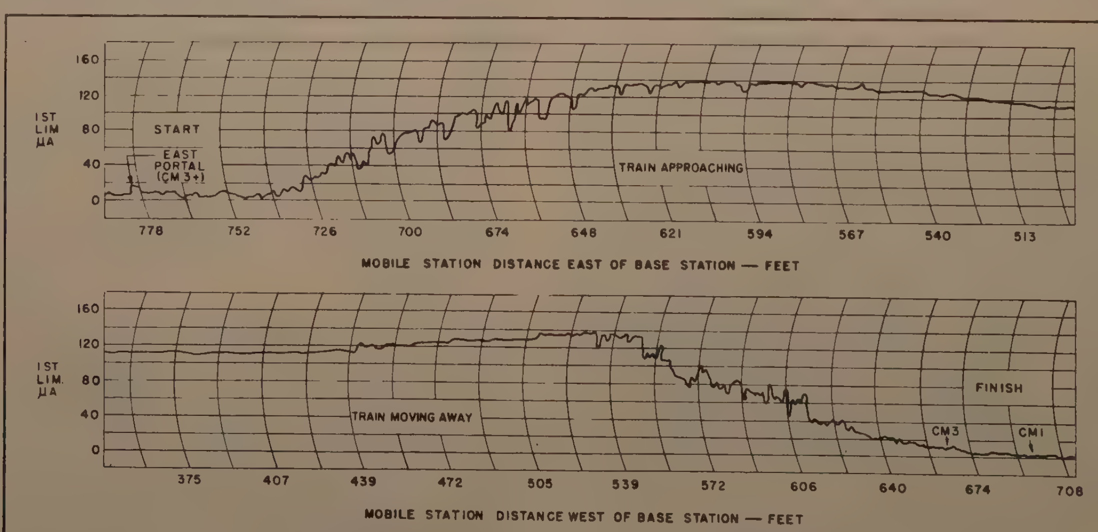

Fig. 6 - Recorded signal received from locomotive.

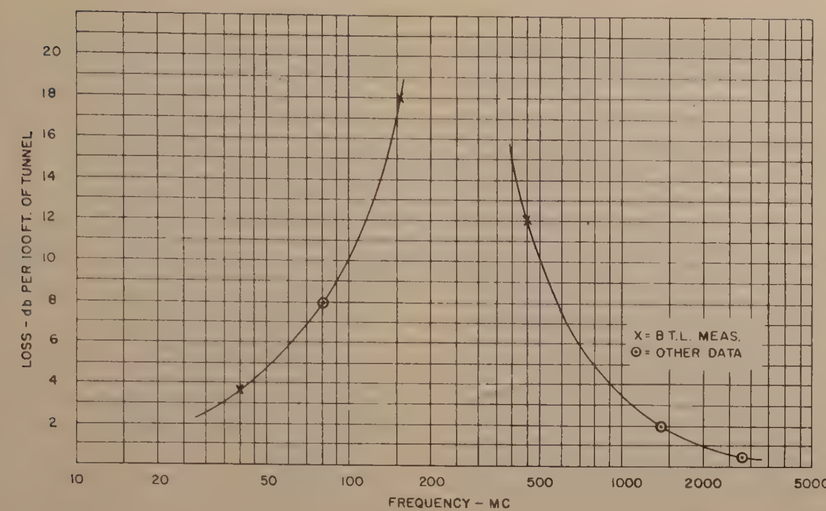

Fig. 7 - RF transmission loss in train-occupied tunnels.

is almost the worst frequency which could be chosen for this type of transmission.

Still another deduction can be drawn from Figure 7. The minimum usable signal for radio transmission of this type is known to be about 120 db below one watt. Assuming that a 30-watt radio transmitter is employed, a total attenuation of approximately 135 db is the maximum which can be tolerated. Therefore, to transmit a distance of one mile, the length of a long freight train, the loss in the tunnel must not exceed about 2.5 db per hundred feet. Allowing for a small margin to insure good transmission under all conditions, the curve of Figure 7 indicates that frequencies above about 25 megacycles and below around 1500 megacycles are not suitable for radio communication in tunnels over any substantial distance by conventional means.

It should be emphasized that the curve of Figure 7 shows the loss which is experienced when a train is in the tunnel. A few tests made with walkie-talkies showed that when a train is not present the attenuation is somewhat less. Tests made by other observers employing small hand cars or trolleys also have indicated lower losses, particularly at the higher frequencies.

Parallel Antennas

The above data indicated that radio coverage in the tunnel could be provided by a series of base stations located within the tunnel and spaced about 1000 feet apart. Obviously, such an arrangement with 13 or 14 base stations in each of the two Hudson River tubes did not appear very attractive. However, the tests suggested another possibility: a transmission line extending through the tunnel fed at one end and having antennas bridged onto it at suitable intervals. This arrangement would have the advantage of employing only inert equipment in the tunnel. Unfortunately, to provide coverage for a tunnel of any substantial length by such means would require a transmission line of very low loss (0.5 db or less per 100 feet) in order to deliver sufficient power to the more distant antennas. Coaxial cables such as 7/8-inch "Styroflex" or "Heliax" having attenuations of this order of magnitude are available but they are quite expensive. Nevertheless, a few tests to determine the feasibility of this method of providing coverage within the tunnel were initiated.

For these tests 2000 feet of RG-8/U coaxial cable was installed in the tunnel. Although RG-8/U cable has a loss at 150 megacycles of some 2.7 db per hundred feet and would not be satisfactory for a permanent installation of this type of any appreciable length, it is inexpensive, easily installed, and readily available. It was thought that the method could be tested out with this type of cable without the expense and difficulties which would be incurred with low-loss structures.

No special precautions were taken in installing the RG-8/U cable. It was mounted in the tunnel by suspending it a few inches below a lighting conduit located on the wall about eight feet above the catwalk. This conduit is visible in Figure 10. One end of the cable was terminated in the base station equipment at the 11th Avenue shaft. From this point the cable was extended westward with five antennas, spaced at approximately 500-foot intervals, connected to it. These antennas, with the exception of the one at the distant end which

terminated the cable, were simple rods nine inches in length designed to provide a relatively low bridging loss to the cable.

The first observation with this arrangement indicated that good transmission was obtained throughout the entire length of the cable. The second and fourth antennas were then removed to provide greater spacing between the antennas and the test was repeated. The results were the same. The remaining antennas were then removed in turn and successive tests were made. It was found that an excellent circuit could be obtained with no antennas at all. In view of this result, the cable was extended another 1000 feet. However, good transmission could not be obtained beyond the original 2000 feet. In an effort to obtain greater coverage, antennas were bridged at the 2000-foot point and every 250 feet beyond. With this arrangement, the range of satisfactory transmission was increased to 2600 feet. It was concluded from these tests that for relatively short tunnels up to about 2000 feet in length, communication can be obtained with a single base station at one tunnel entrance connected to an RG-8/U cable running the length of the tunnel. If base station equipment can be located in the middle of the tunnel, this distance can be increased to about 3800 feet. Bridged antennas will permit those distances to be extended to about 2600 and 4900 feet, respectively.

Transmission Line

The ability of the train station to pick up the signal in the RG-8/U cable and vice-versa immediately led to speculation as to how the coupling was being effected. Consequently, a test was made in which the inner and outer conductors of the coaxial cable were shorted together and energized, against ground, by the base station transmitter. With this arrangement, the coverage was only about one-fourth of that obtained with the cable connected normally. In addition, laboratory tests indicated that RG-8/U cable, which has a single braid outer conductor, has relatively high crosstalk into a similar and closely associated cable. From these data, it was concluded that the field radiated directly from the coaxial cable was mainly responsible for the coverage obtained. It appeared reasonable to suppose, therefore, that a transmission line having an appreciable external field but with considerably lower attenuation than the RG-8/U cable would extend the coverage materially.

Accordingly, theoretical studies of single and two-wire transmission lines were initiated. Because of physical space limitations, such lines must be mounted close to the wall of the tunnel. This results in absorption effects which greatly increase the attenuation over that for such lines in free space. Since it was felt that accurate estimates of such absorption effects could not be made, it was concluded that actual field testing would be required to determine the best arrangements. A single-wire line of the Goubau type was considered, but at a frequency as low as 150 megacycles it was felt that a two-wire line would be more practical. The absorption loss and the field strength at a given distance from a two-wire line both decrease as the spacing between the wires is decreased. Therefore, a compromise between these factors was indicated. Other considerations included first cost and the ability of the line to stand up under the weather conditions likely to be experienced in the tunnel. With these factors in mind, a survey of available two-wire lines having low attenuation at 150 megacycles was made. RG-86/U solid dielectric parallel-pair cable, which is similar to but heavier than television twin-lead cable, and which has an advertised free-space loss of about 0.6 db per hundred feet, appeared to meet the requirements best. Accordingly, 1000 feet of this cable was installed in the tunnel and a series of tests made with it.

The arrangement employed for these tests is shown in Figure 8. The base station

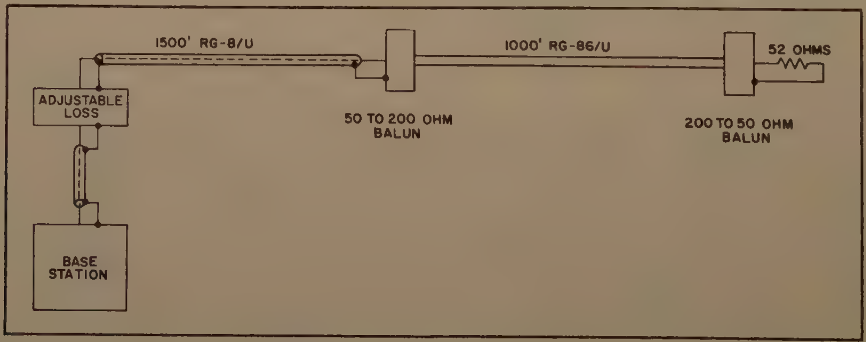

Fig. 8 - Testing arrangement for RG-86/U cable.

equipment was connected directly to 1500 feet of RG-8/U coaxial cable which extended westward along the tunnel wall. The RG-86/U parallel-pair cable was then connected to the end of the coaxial cable through a special impedance-matching transformer (balun). This was employed not only to match the 50-ohm impedance of the coaxial cable to the 200-ohm impedance of the parallel-pair cable but also to convert from an unbalanced to a balanced line. The RG-86/U cable was terminated at the far end in a second impedance-matching transformer and a resistance of 50 ohms. Thus, by substituting a 50-ohm measuring set for the resistance, measurements of the cable loss could be made. A schematic of the impedance-matching device employed, which was constructed locally, is shown in Figure 9.

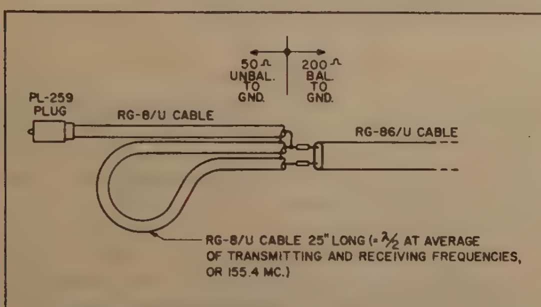

Fig. 9 - Impedance-matching transformer (balun).

The RG-8/U cable, with its loss of approximately 40 db, served two useful purposes. First, it excluded the possibility of any field radiated directly by the transmitting equipment from reaching the RG-86/U cable. Second, it provided attenuation between the base station and the RG-86/U cable. This attenuation, as well as additional pad loss, was required to determine the limits of acceptable transmission.

The RG-86/U cable was suspended from the exposed wall conduit previously referred to by means of marline twine in such a manner that it hung approximately 6 to 10 inches below the conduit. In this position, the parallel-pair was about 7 feet above the catwalk, 12 feet above the rails and 6 to 10 inches from the wall of the tunnel. This placed it about 6-1/2 feet away from the car and locomotive antennas, in a plane about 1 foot below them.

With this test setup, two-way talking and listening tests were made between the base station and a number of trains. Next, the loss of the parallel-pair cable in place was measured and found to be 1.3 db per hundred feet, a substantial increase from the indicated loss of 0.6 db per hundred feet when the cable is in free space. From these data it was determined that with transmission powers of 30 watts, satisfactory two-way communication would be possible with the RG-86/U cable for a distance of approximately 6000 feet.

For a final series of tests, the RG-86/U line was mounted as indicated in Figure 10, in what was considered to be the most favorable location from the standpoint of coupling which physical and clearance requirements in the tunnel would permit. In this position the cable was about 6 inches closer to the car and locomotive antennas, and about 1-1/2 feet higher than for the previous tests, permitting a clear line of sight to the car antennas and a partial one to the locomotive antenna. However, no significant improvement in coverage range was observed.

It was concluded from these tests that satisfactory communication could be established with locomotives, cabooses, and trains in the Pennsylvania Railroad's North River tunnel with RG-86/U wire suitably installed throughout the length of the tunnel and three 30-watt base stations. One of the base stations would be located at each portal and one at the Weehawken shaft, which is about 6000 feet from the west portal and 7400 feet from the east portal. The station at the east portal would be connected to about 4400 feet of wire, that at the Weehawken shaft to about 3000 feet extending eastward and 2400 feet extending westward, and the station at the west portal to about 3600 feet. This arrangement should provide considerable margin over the limiting distance of 6000 feet from the base stations as determined by the tests.

Although the tests were confined to a specific tunnel, it is believed that the solution arrived at would be generally applicable to other tunnels. To be sure, the effect of the tunnel walls upon the attenuation of the wire may vary somewhat with the physical structure of the tunnel as may, also, the coupling between the wire and the train antennas. However, these factors should not be substantially different in other tunnels and should result only in relatively minor differences in the range of coverage attainable with the RG-86/U wire and a single base station.

Conclusion

This paper has described tests looking toward a practical solution to the problem of providing communication with railroad rolling stock in tunnels.

Fig. 10 - Location of RG-86/U cable on tunnel wall.

The results of the tests may be summarized as follows:

1. Frequencies between about 25 and 1500 megacycles are not suitable for radio communication with locomotives or trains in tunnels of any substantial length by conventional means.

2. Communication in the 152-162 megacycle band between base stations and trains in tunnels, can be accomplished by connecting a base station to a closely spaced two-wire line extending through the tunnel and mounted about six inches from the tunnel wall in a position to provide as close coupling to the antennas on the trains as clearance or other railroad requirements will permit.

3. An arrangement of the type described in (2) above employing RG-86/U wire and a 30-watt base station will provide coverage for a distance of approximately 6000 feet in the North River tunnel of the Pennsylvania Railroad.

4. It is believed that the coverage which could be obtained with this arrangement in other tunnels would not be materially different.

It should be pointed out that our efforts were directed toward determining a practical means for providing radio communication with railroad rolling stock in tunnels. This was to be accomplished utilizing equipment and facilities known to be available and without employing special mobile station arrangements. It is not suggested that the arrangement arrived at is the best solution to the problem nor is it even suggested that RG-86/U wire is the best possible wire to use. Further research and experimentation might well reveal a more efficient method or type of wire line. However, such a study would be time-consuming and expensive. In view of the practical answer already arrived at, it does not appear to be justified at the present time.

In conclusion, the authors wish to express their appreciation to their associates, Messrs. H. J. Bergmann and R. V. Crawford, for their suggestions and assistance in conducting the tests, and to Mr. F. B. Llewellyn for his advice and encouragement. Also, the cooperation of the engineers and other personnel of the Pennsylvania Railroad is gratefully acknowledged.

Bibliography

1. Ernest Dahl, "Rock Island Radio Tests", Electronics, Vol. 18, pp. 96-102; May 1945.

2. J. P. Shanklin, "VHF Railroad Communication in Tunnels", Communications, Vol. 27, pp. 16-19; June 1947.

3. G. H. Leversedge, "The Problems of Radio Communication with Moving Trains", British IRE Jl., Vol. 7, pp. 157-163; July-August 1947.

4. J. B. Lovell Foot, "Transmission Through Tunnels", Wireless World, Vol. 56, pp. 456-458; December 1950.

A SEMI-AUTOMATIC TUNING HIGH FREQUENCY COMMUNICATIONS EQUIPMENT

M. C. Dettman

FEDERAL TELECOMMUNICATION LABORATORIES
A DIVISION OF INTERNATIONAL TELEPHONE AND TELEGRAPH CORPORATION
NUTLEY, NEW JERSEY

This paper describes a high frequency two way communication equipment designed for vehicular mounting. A high degree of frequency accuracy and stability along with simplified semi-automatic transmitter tuning is featured. In addition to voice and code transmission and reception capability, facilities for frequency shift keying and teletype operation without the need of additional conversion equipment or power supplies are provided. A telephone and ringer circuit operating over the two wire remote control line is incorporated. Photographs and block diagrams of the various units are shown.

The rapid pace of communications techniques in the high frequency range during the last decade has resulted in the demand for improved communications equipment. Among the requirements for such materiel are those of higher frequency stability, higher radiated power output, improved over-all efficiency, greater flexibility, ease of operation, compactness, and a high degree of reliability. Some of these objectives are mutually incompatible and the design engineers must carefully weigh these and the economic and time limitations imposed.

In the development of Radio Set AN/MRC-55, we have incorporated the aforementioned general design objectives. Figure 1 shows Radio Set AN/MRC-55 mounted in the vehicle. This radio set provides two-way, high frequency vehicular communications consisting of CW signals, phone and frequency shift keying, or a combination of the latter two simultaneously. The frequency spectrum covered is from 2 mc to 30 mc.

A block diagram of the equipment is shown in Figure 2. Nominal power output of the transmitter is 100 watts carrier into a 50-ohm resistive load. Alternatively when operating directly into an antenna the power level fed into a simulated 15-foot whip is dependent on frequency, being better than 85 watts above 6 mc and gradually decreasing with frequency below 6 mc. The frequency accuracy under the stabilized condition after warm up is ±200 cycles for all specified variations of input voltage, power frequency, shock, vibration, humidity, and for temperature variations for Class I equipment (-54°C to +65°C). The receiver is a high performance unit capable of phone, CW and FSK reception. It includes an integral frequency shift converter. Telephone and ringer facilities are provided for between the radio set location and a field remote control which may be located up to one mile distant. Input voltage for the radio set may be either 28 volts dc or 115 volts, 60 cycle ac.

The transmitter signal portion of the radio set consists of eight major blocks as shown in Figure 3. These units are housed in a cabinet 29 in. wide x 13-5/8 in. high x 17-1/2 in. deep. In order to make the unit submersion proof, ventilating louvers may be readily closed. The r-f signal is generated in the variable frequency oscillator consisting of two tubes and two diode reactance modulators. This signal is then fed to the amplifier-modulator section to a buffer-driver tube and a 4X250D power amplifier tube. The r-f signal at the PA Tank is then fed to the antenna tuner and thence to the antenna. Since frequency stability and accuracy requirements are greater than available from a readily designed master oscillator, a frequency synthesizer consisting of a reference oscillator and a stabilizer unit are utilized to obtain the necessary degree of precision. The variable frequency oscillater may be operated either with or without frequency correction information from the stabilizer so that tube or component failures in the more complex synthesizer section of the transmitter will not cause carrier failure, thus greatly enhancing reliability and maintenance of continuous communication. For voice communication, microphone signals are fed to the speech amplifier and thence to a pair of 4X250D high level modulators. The choice of these tubes for both modulator and r-f amplifier portions of the equipment makes for conservative operation and ease of maintenance, further enhancing reliability. Telegraphic hand-key signals and teletype signals are fed via the keyer circuits to appropriate points in the transmitter circuits to generate CW hand-key signals or frequency shift-keyed signals for teletype operation. The mark to space frequency separation is adjustable.

In order to achieve ease and simplicity of operation, automatic tuning is employed for all r-f circuits following the variable frequency oscillator. This tuning is under the control of the electronic control unit.

A typical step-by-step operator's procedure for setting up a new communication channel illustrates the simplicity of operation. The operator sets the service selector switch for type of operation; i.e., phone CW, FSK, and turns the main power switch to the primary power, 28 volt dc or 110 volt 60 cycle ac, as required. He then sets the band switch to the appropriate band for the

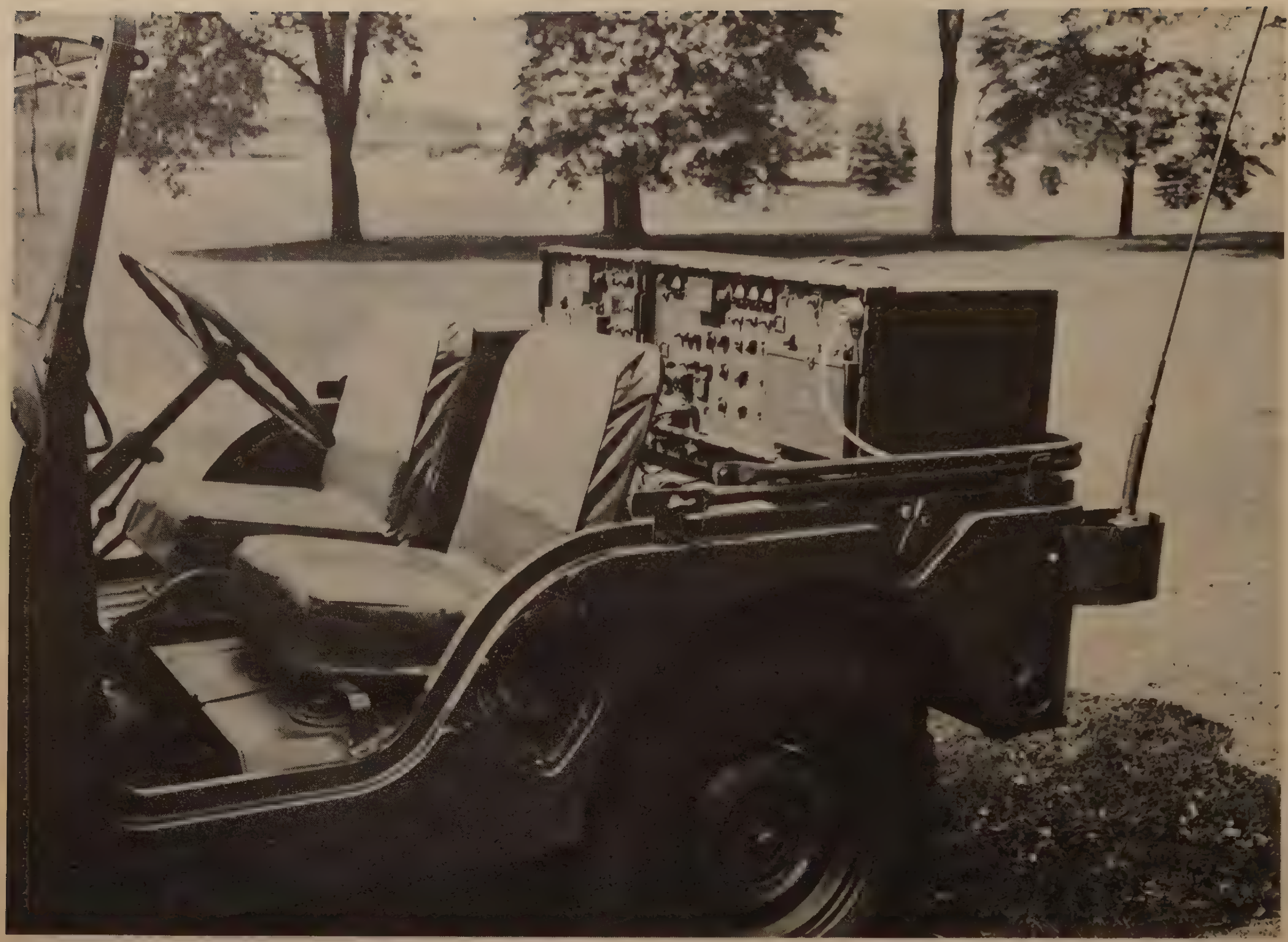

Fig. 1 - Radio set AN/MRC-55 mounted in vehicle.

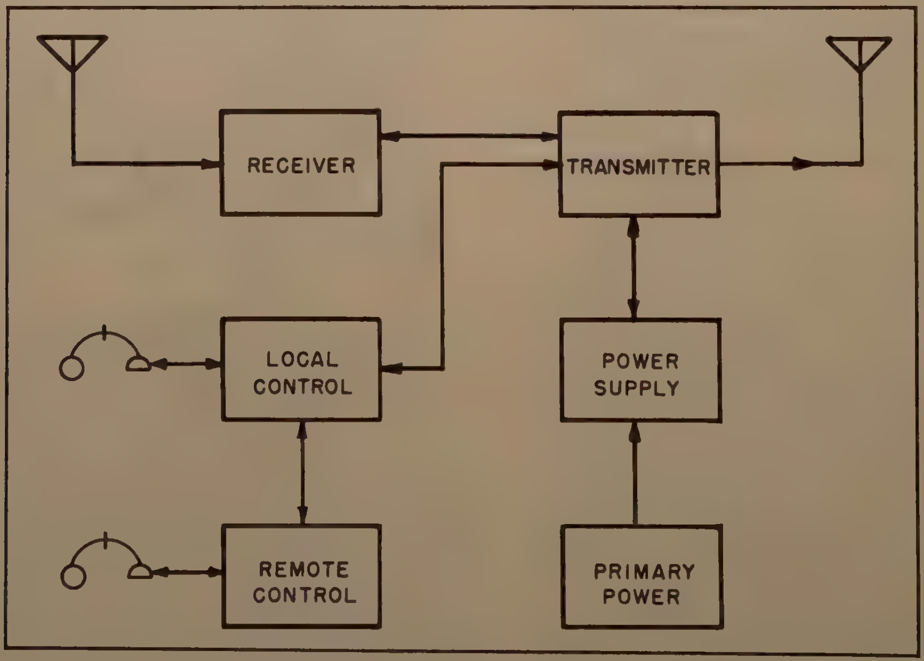

Fig. 2 - Simplified block diagram of AN/MRC-55.

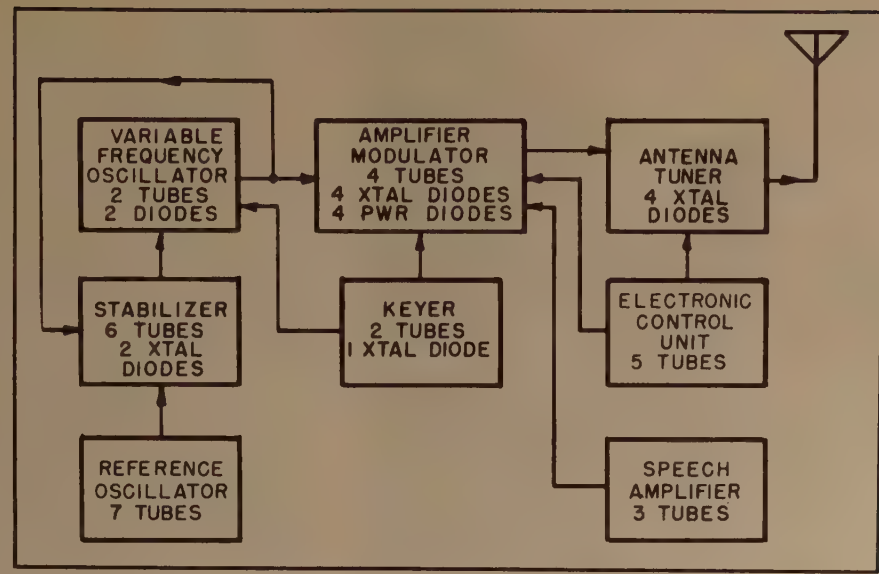

Fig. 3 - Simplified block diagram of transmitter.

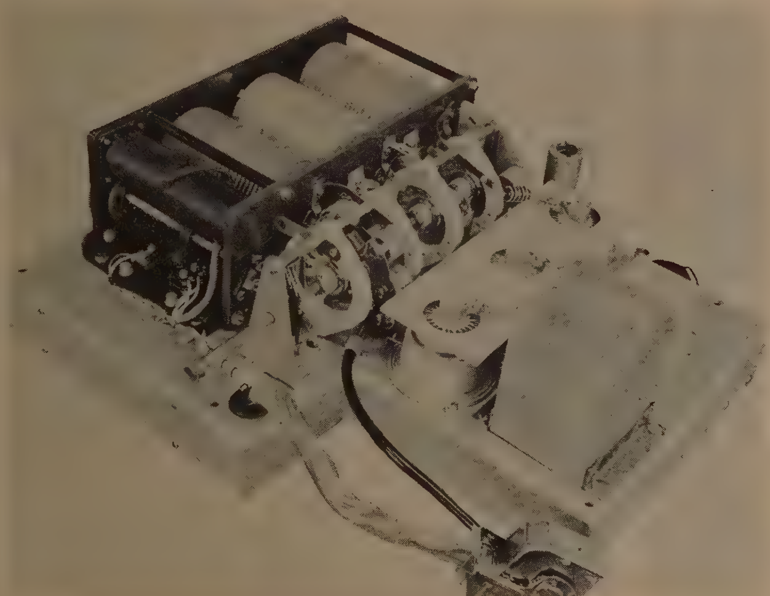

Fig. 4 - Amplifier-modulator chassis.

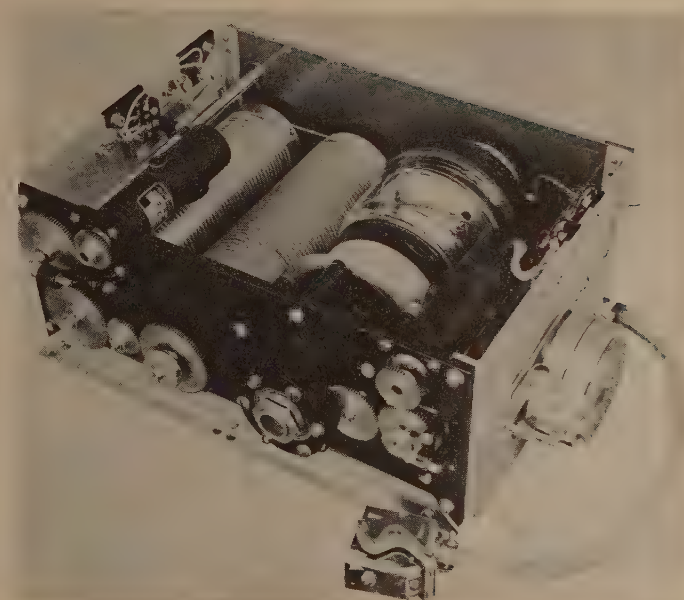

Fig. 5 - Automatic antenna tuner.

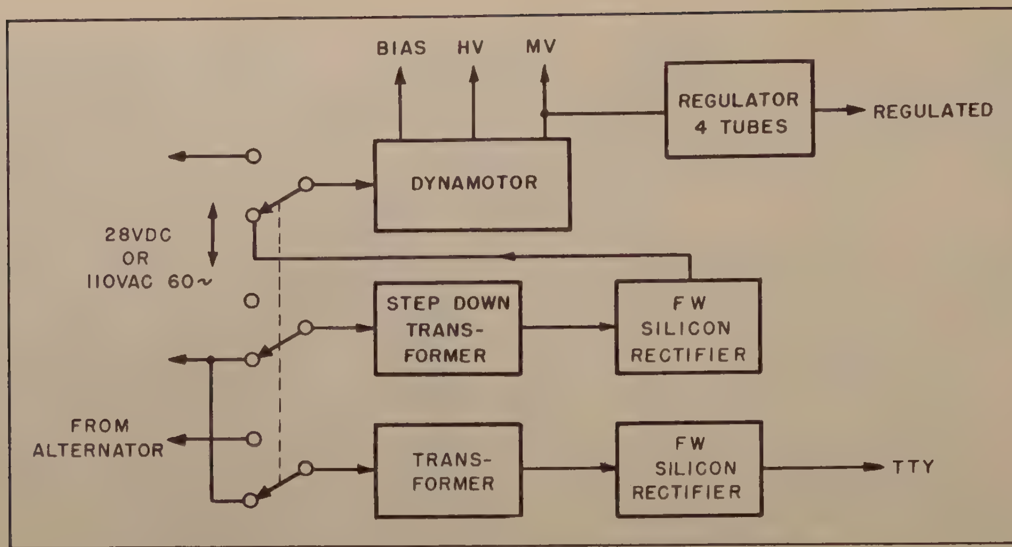

Fig. 6 - Simplified block diagram of power supply.

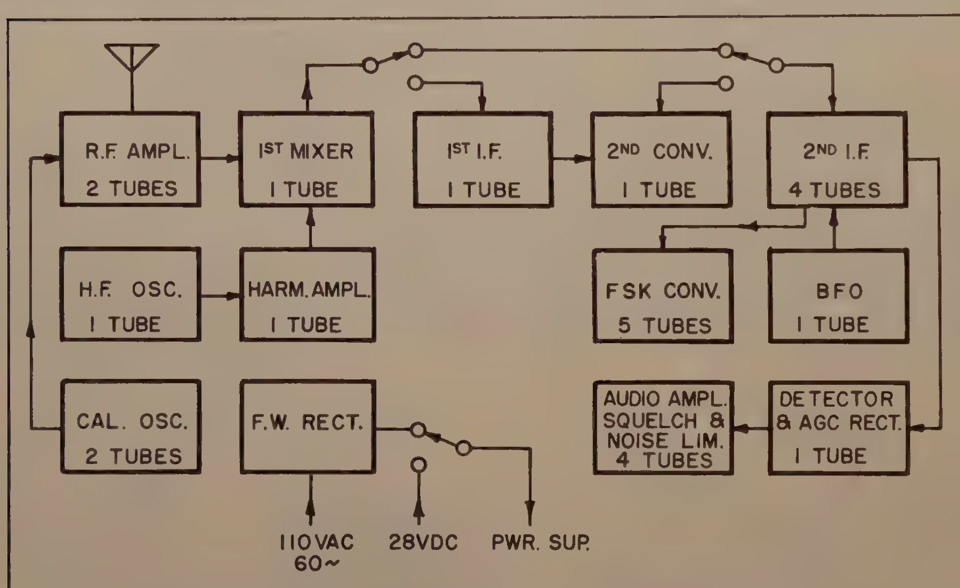

Fig. 7 - Simplified block diagram of receiver.

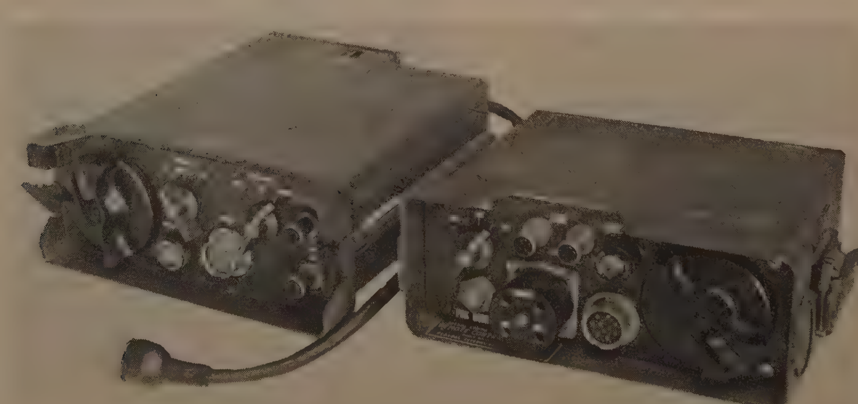

Fig. 8 - Remote control, telephone and ringer facilities.

frequency he is about to set up. The next step is to set up the frequency in the synthesizer by means of direct reading decade dials. No interpolation or calibration charts are used. Having set the frequency in the synthesizer, the variable frequency oscillator is locked in much the same manner that an FM receiver using a tuning meter is tuned to a station. The automatic tuning button is now depressed and the r-f amplifier stages and the antenna circuit are resonated automatically after which the transmitter is ready for push-to-talk operation or such service as has been selected.

Figure 4 illustrates the compact structure of the amplifier modulator chassis. Band switching is accomplished by switching appropriate fixed tuning and coupling capacitors. Tuning is performed by a set of ribbon type variable inductors. This has resulted in considerable reduction in volume for this section as compared to that which would have been required for a coil switching—variable capacity type tuner.

A view of the automatic antenna tuner is shown in Figure 5. Resonance and loading is adjusted by means of a variable vacuum capacitor and a ribbon type variable inductance. Various materials were investigated by means of life tests for adequate performance in the variable inductances used in the amplifier and antenna tuner coils. The material currently used for this purpose is 0.015 in., hard-drawn, fine silver ribbon. Even after determining the optimum material, we felt it desirable to increase coil diameter and arrange for single flexing wind-up to give still greater life expectancy for the ribbon coils.

The power supply for the transmitter is housed in a cabinet 29 in. wide x 10 in. high x 17-1/2 in. deep. This size permits easy stacking with the transmitter cabinet. The ventilating louvers have covers which may be readily closed in order to make the unit submersion proof. Figure 6 shows the block diagram of the power supply. This unit supplies all transmitter requirements plus teletype loop current for either a-c or d-c operation at the flick of a switch.

A somewhat novel approach for the power supply has been used in the interest of weight saving, simplicity and its attendant reliability. Since a dynamotor was required for d-c operation, it was proposed that the same dynamotor be used for a-c operation. This required the incorporation of a 28 volt 50 ampere d-c supply consisting of a rugged step-down transformer and a compact full wave silicon rectifier to feed the dynamotor. This approach has resulted in the saving of 15 components, some of them high voltage units, and considerable space in the over-all design. The requirement of dynamotor brush inspection every 500 hours of operation as indicated on a dynamotor running time meter is a small price to pay for all of the advantages accrued through the design approach used.

The receiver used with this radio set may be operated as a part of the over-all radio set or individually. The frequency range covered is from 2 mc to 32 mc. It is capable of receiving CW, modulated CW, phone, and frequency shift keyed signals. An FSK converter for directly keying a teletype loop circuit is incorporated. The over-all size is 10 in. wide x 11 in. high x 15 in. deep. The cabinet is completely enclosed and submersion proof. It may be operated from either 28 volt dc or 110 volt 60 cycles ac. A block diagram of the receiver is shown in Figure 7. In order to achieve high stability, low spurious, and a high degree of selectivity, several design features are worthy of mention. The four-band receiver uses two stages of r-f preselection. An unswitched local oscillator in conjunction with a tuned harmonic amplifier is utilized to generate the i-f frequency utilized for reception of the 2 mc to 8 mc range. Double conversion with a crystal-controlled second converter is utilized in the frequency range above 8 mc. The first i-f frequency over this range is at 1500 kc. Two-step variable selectivity is employed at the 455 kc i-f frequency. An adjustable squelch and a noise limiter is employed so that an operator monitoring a standby frequency need not continually listen to atmospherics and noise. A crystal calibrator is incorporated to permit dial calibration accuracy of better than 0.05 per cent at any point on the dial.

The boxes for remote control, telephone and ringer facilities are shown in Figure 8. These submersion-proof units are very similar to the type AN/GRA-6 control boxes.

Accessory equipment such as headsets, handset, microphone, loudspeaker, and telegraph key are furnished. Antennas consisting of a 15-foot whip, a 30-foot whip, and two long-wire antennas are also supplied.

Each radio set has, in addition, a conversion vehicular power generator system to replace the standard low capacity type normally installed in the vehicle.

Total volume of the radio set including two receivers, transmitter, power supply, and remote units is approximately nine cubic feet. The weight is 450 pounds. Fifty-six tubes consisting of 17 types as well as 19 germanium diodes and 10 silicon diodes are used in the overall system. Full power drain from the vehicle, key down, is 1375 watts.

The radio set described fulfills the need for a modern high performance vehicular communications equipment.

NEW DEVELOPMENTS IN TWO-WAY COMMUNICATIONS

A. A. Macdonald
Motorola, Inc.
Chicago, Illinois

If you literally interpret the title of this paper you might think that I am going to try to cram the total experiences of approximately 56,000 man hours of development into a 25 minute talk. Obviously this would be quite impractical. I can, however, condense the results into a short report, giving you the highlights of three significant new developments in the two-way communications field.

The three developments to be described are, the Motorola "Private Line" radio system, a transistorized dynamic microphone for mobile communications, and a new line of transistorized "Handie-Talkie" FM radiophones.

"Private Line" Radio Systems

First let's consider the new Motorola "Private Line" radio system. For some time it has been evident that the development of a coded squelch system to replace the conventional carrier squelch would essentially eliminate all types of nuisance interference, including long range skip interference, which is predicted will reach its peak sometime in 1957.

After investigating a large number of proposed systems it was finally decided that the system to be described here would provide the maximum sensitivity and reliability. In setting up specifications for this system it was decided that if the system was to be used to replace the conventional squelch, the sensitivity of the coded squelch should be at least equal to if not greater than the sensitivity of the conventional squelch system. After extensive analytic and empirical work it was determined that the coded squelch system which would yield the best results would be comprised of a simple tone generator in the transmitter and a tone decoder in the receiver. In this system the transmitter is continuously modulated with a low frequency tone and in the receiver the detected tone is used to hold the receiver squelch open. Tone modulation is continuous so that the system is "fail-safe"; in other words, if the tone at the receiver disappears due to loss of signal or to capture effect the receiver squelch closes. This is in contrast to the average tone system where the receiver is held open by a carrier squelch, even if the tone which initiates the call disappears. By the use of low frequency tones it is possible to make the coded squelch system as sensitive as the best carrier squelch system yet devised, and it is not necessary to incorporate a squelch control. The presence or absence of the tone is the only sensing required of the receiver tone decoder. In contrast to this the average carrier squelch system must provide a squelch control to permit adjustment for various conditions of receiver gain and external interference. The new coded squelch system does, however, provide a switch to permit disabling the squelch either to check operation of the receiver or to monitor the channel.

In order to generate the low frequency precision tone, it was decided to use the tried and proven Motorola vibrasender electro-mechanical reed assembly, which has over the years proved to be an extremely reliable component. To detect the tone, it was decided to use the companion vibrasponder reed assembly which has also been developed into a highly reliable device.

Figure 1 shows a block diagram of the phase modulation transmitter incorporating the "Private Line" radio precision tone generator.

Figure 2 shows a block diagram of the frequency modulation receiver incorporating the "Private Line" radio precision tone selective detector.

Figure 3 summarizes the basic specifications of the coded squelch system.

It doesn't take much thought to realize that the "Private Line" radio development is unique in that it provides the user of two-way communications with a fast, automatic, and "fail-safe" squelch system which will not respond to nuisance

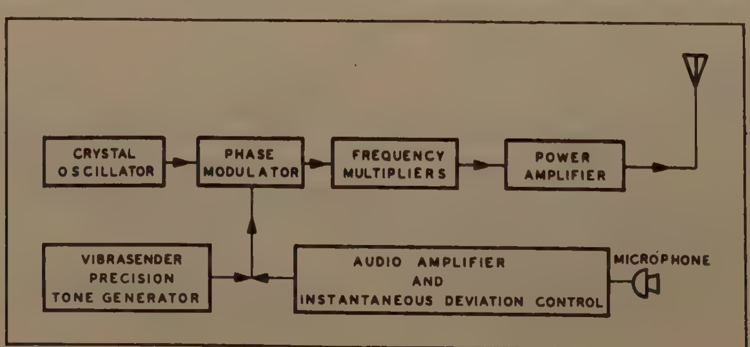

Fig. 1 - Block diagram of "Private Line" transmitter.

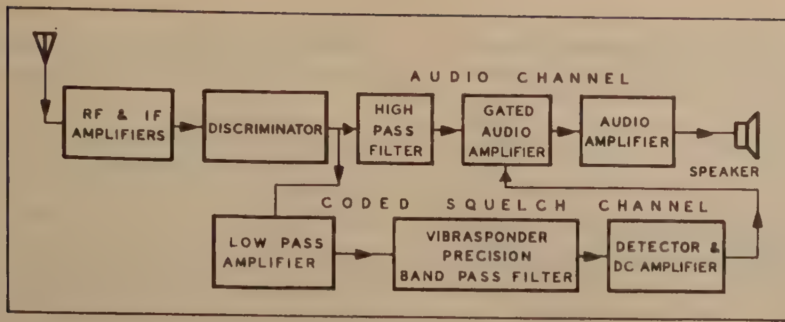

Fig. 2 - Block diagram of "Private Line" receiver.

TRANSMITTER

TONE GENERATOR FREQUENCY STABILITY -
TOLERANCE ±0.15% FROM -30° TO +80°C.

TONE CHANNEL SPACING -
APPROXIMATELY 3.6%, LOWEST TONE 100 C. P. S.

TONE MODULATION -
1 TO 2 KC. DEVIATION FOR 15 KC SYSTEM DEVIATION.

RECEIVER

SQUELCH SENSITIVITY -
SQUELCH OPENS UPON RECEPTION OF SIGNAL MODULATED WITH PROPER TONE WHICH PRODUCES 3 DB OR LESS OF QUIETING.

TONE CHANNEL SELECTIVITY -
SQUELCH WILL NOT OPEN UPON RECEPTION OF TONE MORE THAN 2% FROM f_0 REGARDLESS OF TONE LEVEL.

TONE DECTECTOR FREQUENCY STABILITY -
TOLERANCE ±.25% FROM -30° TO +80°C.

Fig. 3 - Characteristics of "Private Line" equipment.

interference. One of the biggest problems which had to be solved in this development was the reduction of tone distortion, both in the tone generator and in the transmitter modulator. In this system, the low frequency tone is made inaudible to the listener by filtering it out of the receiver audio system. It is evident, however, that if appreciable distortion were present in the system, the harmonics developed would fall within the voice band and could not be filtered out. The presence of the harmonics alone would make the tone quite audible even if the fundamental were completely eliminated.

It has been extremely interesting to note that experienced users of two-way radio equipment who have installed Motorola "Private Line" radio equipment find that the range of their station has generally been increased due to the fact that the "Private Line" squelch system is always "feathered", whereas in the conventional squelch system a control is available to the operator to set as he sees fit, and he may thereby inadvertently reduce his range by a factor of about two. Also, of course, since the new coded squelch system hears only its own calls and is unobtrusively quiet the rest of the time, the operator is much more alert to all incoming calls. I would not advocate that one remove the control from the conventional squelch system, but I do wish to point out that the removal of the requirement for the control in the "Private Line" system permits an increase in the effective range of the average two-way mobile radio system.

It has always been said that a picture is worth ten-thousand words. By the same token I believe that a recording of an actual "Private Line" system in operation is worth more than all the words I can cram into my few minutes here. Therefore, let's listen to a short tape which has been recorded directly from receivers in an actual system. This tape shows what can be heard daily in a busy taxicab channel, both with and without a "Private Line" coded squelch system.

It should be realized that "Private Line" radio can be used to reduce or eliminate nuisance interference, whether it be in co-channel system operation, which is common in the oil and special industrial fields, or whether it will add nuisance protection to a channel offset system, as is being proposed in some of the heavily used spectrum areas. In the low band, "Private Line" radio codes are being allocated in a planned pattern to achieve a maximum reduction of skip interference.

At the present time it is possible to assign ten different codes in the coded squelch system, and there is possibility of further expansion in the future. It should be evident that the addi-

tion of squelch codes adds a new degree of freedom to the design of two-way mobile radio system. "Private Line" radio systems have now been tested in the field for a period of two years and have been found to provide the highest degree of reliability.

"Private Line" radio provides a new dimension in mobile radio system design. Since the system is automatic in operation, is suitable for use in rapid dispatching, and since it does not respond to nuisance types of interference, "Private Line" radio has proven to be a new tool in mobile radio systems design. In addition to radio frequency and geographic spacing we now have "Private Line" radio tone frequencies.

Transistorized Dynamic Microphone

It has been evident for many years that the development of high quality two-way radio communications was being hampered by the widely used carbon microphone. People have tried again and again to use various types of high quality microphones in mobile applications. The basic problem remained, however, that the high quality microphones have low electrical output relative to the carbon microphone and, therefore, require considerable gain between the microphone and the modulator of the mobile radio transmitter. If the low output microphone is connected to the radio equipment through a cable of appreciable length the problem of eliminating hum pickup from this cable becomes a serious one indeed. You might well ask, "Where do the currents come from that create the hum field which causes so much trouble in the mobile vehicle?" The answer is fairly simple. The radio equipment itself is responsible for a highly distorted current wave form fed either to a vibrator or a dynamotor supply. In addition the automotive ignition system, generator, and various indicator elements all add their impulse currents to a complex current picture in the vehicle structure. Suffice to say that heretofore the many efforts which were made to incorporate a superior microphone into the mobile radio system met various degrees of failure due to the severe requirement imposed upon the microphone shielding and equipment installation.

However, this whole picture has changed with the availability of reliable audio transistors. The audio transistor makes possible the development of a dynamic microphone which includes a transistor pre-amplifier within the microphone case and thus can have a high output and can be interchangeable with its carbon microphone predecessor. The use of a dynamic transducer element eliminates the basic problems of distortion inherent in the carbon microphone. Furthermore, the dynamic unit is relatively insensitive to hum fields. The transistor pre-amplifier permits obtaining a high output level so that hum pickup in microphone cables is not a problem. Since the carbon microphone required a battery source it has been possible to develop a transistor microphone which is completely interchangeable with its carbon predecessor, the carbon button current source can also be used as a current source for the transistor pre-amplifier.

As soon as good audio transistors became generally available we set up a program to develop a reliable transistorized microphone. The biggest problem lay not in the transistor pre-amplifier, as you might think, but in shaping the response characteristics of the dynamic element to match the communication requirements. This shaping is essential to produce a pleasing output and at the same time eliminate undesired vehicle and wind noises. As it was finally designed, the microphone has a fairly flat response over the range of 300 to 4000 cycles. Frequencies outside this band are attenuated quite rapidly. This shaping was accomplished by mechanical adjustments on the dynamic transducer itself.

Figure 4 shows a disassembled view of the transistorized dynamic microphone. It should

Fig. 4 - Transistorized dynamic microphone.

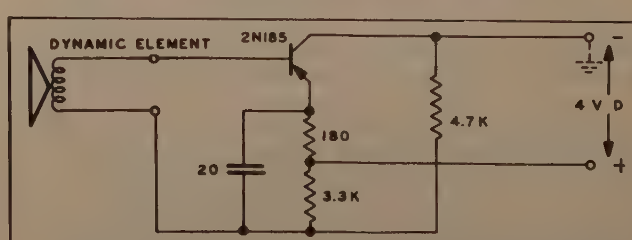

Fig. 5 - Schematic diagram of transistorized dynamic microphone.

be noted here that all of the elements comprising the transistorized dynamic microphone have been designed to function properly after a 200 hour humidity test.

Figure 5 shows a schematic diagram of the microphone and graphically illustrates the simplicity of the device. This transistor microphone has been in production for about six months.

To date the field reports have all been excellent and the unit is gaining wide acceptance.

In order to satisfy those of you who may wonder whether or not this development is worthwhile, please listen to a short tape showing the relative quality of the carbon versus the dynamic microphone as recorded from an actual mobile system.

New Line of Transistorized "Handie-Talkie" Portable Radiophones

The ultimate design goal in portable two-way radio equipment is to provide efficient communications in the smallest and lightest possible package. More power output can always be achieved if the size and weight of equipment are increased. On the other hand, equipment can be made smaller and lighter by sacrificing RF power output and battery life.

Though transistors have not reached the stage in their development where they can be applied across-the-board in all communications equipment, they have been proven suitable for application in the portable field where they provide tremendous advantage in terms of small size, and reduced battery drain.

In order to take full advantage of the economies of size, weight and battery drain made possible by the application of transistors to portable equipment, it has been necessary to completely redesign our entire line of portable equipment in both the 25 to 54 and 144 to 174 Mc. bands. The following major design goals were established:

1. Increased r.f. power output.
2. Increased audio power output.
3. Reduced size and weight.
4. Reduced battery drain.
5. Increased reliability.

In addition it was desired to provide increased accessibility for ease of service and modular construction, both for ease of service and for maximum flexibility in numerous different applications.

You will see how well these goals have been met. Suffice to say here that this line of transistorized portable equipment far exceeds any equipment ever before available anywhere with respect to small physical size, coupled with improved electrical performance.

Since the entire line of new portable equipment represents a tremendous development effort as well as introducing many new techniques, and since our time here is very limited, I believe the best approach to take in discussing this development is to describe the equipment itself with the aid of slides, pointing out some of the important engineering features and then review quickly a few of the development problems.

Figure 6 shows the three basic units in Motorola's new line of transistorized "Handie-Talkie" FM radiophones. The "H" series for maximum portability, and the "P" series for high r.f. power output. Both series are available in the 25-54 Mc. and 144-174 Mc. bands. I have several pieces of this equipment here for your examination after the meeting.

The new "Handie-Talkie" unit is transistorized as far as the present state of the art permits. The receiver for instance has only three tubes in the r.f. and OSC. section, the remainder

Fig. 6 - Hand "P" series "Handie-Talkie" portable units.

of the receiver circuitry contains 8 transistors. The transmitter contains one transistor and 6 or 7 tubes. Two additional transistors are added for loudspeaker operation.

Basically, each of the units is comprised of two parts, a radio unit and a battery pack or power supply, as shown in Figure 7. The battery pack or power supply can be snapped on to the radio unit in a matter of moments. The same radio unit may be plugged into any of the various power packs. For example there are two dry battery packs available in the "H" series, one being extremely small and light weight and the other having approximately the same cost battery comp-

Fig. 7 - "Handie-Talkie" radio and detachable nickel cadmium battery pack.

liment, but providing considerably greater battery life. The lightest battery pack will last two days on a RETMA 10% transmit duty cycle. The heavy pack will last five days on the same duty cycle.

On the light duty cycles of about 1% transmit normally encountered in the field, the life of the battery pack would be extended to about 1 week and 2 weeks respectively. In addition to the dry battery packs a nickel cadmium battery pack is available which uses a transistor power switch converter to convert the 6 volt battery supply voltage to the higher operating voltages required by the unit. This power pack is the one shown in Figure 7. The radio unit and the transistor power switch supply have also been designed to plug into any 6 or 12 volt automotive

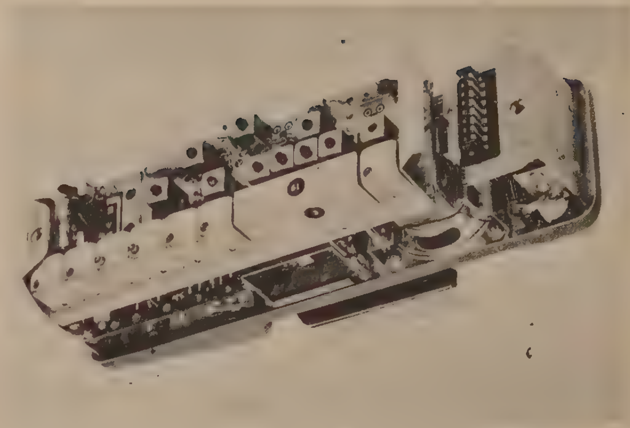

Fig. 8 - "Handie-Talkie" radio unit.

power source. When connected to the 6 or 12 volt automotive system the nickel cadmium battery is kept on trickle charge so that the portable unit is ready for instant use when carried from the vehicle. In every case the power pack plugs into the radio set; a short length of cord is provided on the power pack so that the radio unit may be separated from the pack to facilitate service.

The radio unit itself is shown in Figure 8. You can see the plug at the left end of the unit which connects to the power pack. The rear of the loud speaker can be seen just to the right of the power plug. The deck in plain view is the receiver deck. The transmitter deck is located just below it. In order to obtain access to the under side of the receiver deck it is only necessary to loosen four captivated screws and then the complete radio unit can be unfolded as shown in Figure 9. Figure 9 clearly shows the underside of the receiver deck and one side of the $1\frac{1}{2}$ watt transmitter deck. In order to obtain higher power output, a power amplifier module may be added to obtain 8 watts in the low band and 5 watts in the high band. In the unit shown the power output is $1\frac{1}{2}$ watts in the low band and 1 watt in the high band.

Fig. 9 - "Handie-Talkie" radio unit unfolded.

Figure 10 shows the transistor power switch which is used to commutate either 6 or 12 volts to obtain the high voltages required to operate the receiver and transmitter. When this power switch is plugged into an external battery source

Fig. 10 - "Handie-Talkie" transistor power switch.

such as an automotive supply, it provides a trickle charge to keep the nickel cadmium battery fully charged.

Figure 11 shows a block diagram of the "Handie-Talkie" radiophone receiver and transmitter. In the high band the receiver employs double conversion, and in the low band single conversion is used. The only difference between these receivers is the r.f. module which can be interchanged between units. The low IF frequency is 455 Kc.; a sealed electrical "Permakay" filter at 455 Kc. provides the receiver selectivity characteristics which can be changed to fit channelization requirements. This feature makes receiver modification for split channel operation extremely simple.

The total receiver power drain is 500 milliwatts. 440 milliwatts of the total drain is consumed by the three tube stages. The basic receiver sensitivity is one microvolt in the high band and ½ microvolt in the low band. The audio output of the handset models is 3 milliwatts. When a speaker is used a Class B transistor audio power amplifier is added which boosts this output to 300 milliwatts to the loud speaker. Note also that all models incorporate a squelch circuit and squelch control.

In the transmitters the tube lineup varies slightly between the high and low band units. The transmitter tube lineup consists of five 1AD4's and three 6397's or 6526's. The transmitter audio uses a single 2NJ2G or a 2N138 transistor. The portable transmitters all include instantaneous deviation control to prevent overmodulation and a modulation splatter filter to protect the adjacent channel user from modulation splatter. This is particularly important in split channel systems now that we have 8 watt portable units.

It is interesting to note in passing that each of the receiver and transmitter modules are interchangeable so that a cross-band unit can easily be built.

The following is a relative comparison between previous Motorola portable equipment and the new line:

1. The size has been reduced 30%.

2. The weight has been reduced from 30 to 60%, depending upon the particular model. The lightest unit available weighs 7½ lbs.

3. Power drain has been reduced and battery life extended so that operating costs have been reduced more than 60%.

4. Audio power output to the speaker has been increased three fold.

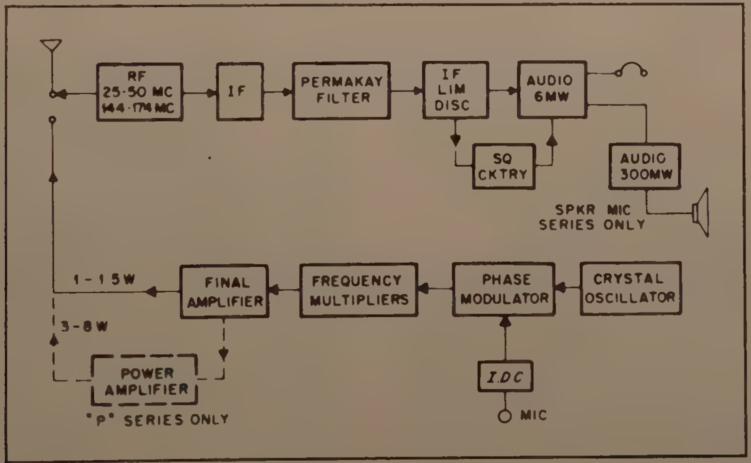

Fig. 11 - Block diagram of "Handie-Talkie" receiver and transmitter.

5. Transmitter power output has been increased up to 20 times. On the smallest unit the power output has been increased approximately 4 times.

6. The new light weight "H" series provided with a speaker and microphone weighs only 9 lbs. 5 oz., and outperforms the older pack set which weighs 22 lbs.

The biggest design problems encountered in this development were associated with the transistor circuitry. As you all know, the characteristics of production transistors are subject to rather wide variations; this is particularly true of the higher frequency transistors. In addition the characteristics of all transistors are subject to variation over the temperature range considered normal for portable equipment. For these reasons it was necessary to put a great deal of engineering time and effort into the design of IF and audio circuits which would tolerate these variations without loss of performance. This design effort has been quite successful as shown by the fact that the first production units were shipped 6 months ago and no field failures due to transistors have been reported to date. In addition, this portable equipment passes severe environmental tests without encountering difficulties due to variation in transistor characteristics over a temperature range.

It is interesting to note here that the new transistorized portable units incorporate all the basic features of our standard mobile equipment. It is planned in the future that transistorized portable models will be available incorporating Motorola "Private Line" squelch system. This portable equipment has now been in production long enough to give assurance that it is extremely reliable and represents a big improvement in communications and reduced operating costs for the user.

Conclusion

This talk has highlighted the important points in three new developments in the two-way communications field. First, we discussed the new "Private Line" radio system which functions to essentially eliminate all types of nuisance interferences. Second, we reviewed briefly the development of a transistorized dynamic microphone for improved mobile communications, and finally we discussed the development of a new line of transistorized portable equipment. It is concluded that each of these developments takes a big step toward better communications efficiency for the user of two-way mobile and portable radio.

TRANSISTORIZED COMMUNICATIONS RECEIVER

Seymour Schwartz, President
Transistor Applications Company
Boston, Massachusetts**

Summary. The purpose of this project was to use silicon transistors in place of vacuum tubes in all sections following the mixer stage of a military type communication receiver. The hybrid receiver built, while keeping the desirable characteristics of the vacuum tube receiver also provided for an increase of audio power and a reduction of battery power drain.

Transistors have been used successfully in all sections following the mixer of a 500-Kcps. to 32-Mcps. military, vehicular-type radio receiver originally designed with all vacuum tubes. The receiver provides reception of radio-telegraph, radio-telephone and single-channel, frequency-shift radio teletype signals. Operation is from a 24-volt D.C. System. This receiver is a superheterodyne of the multiple conversion type. See Fig. 1 (Schematic).

The hybrid receiver achieves a reduction of battery power drain by one-third while increasing the original audio power output by a factor of five. It incorporates an AGC system capable of controlling both the vacuum-tube and transistor sections simultaneously. The i-f bandwidth is made constant for variations in signal strength by the use of mechanical filters. Sensitivity is comparable with that of the electron-tube model as is the voltage-regulating action.

The sections transistorized were the i-f and audio amplifiers, the AGC system, calibrator, squelch and beat-frequency oscillator. Twenty-five tubes were replaced with 22 transistors and 10 diodes. Silicon transistors are used exclusively except for two Germanium power transistors in the audio section. The transistorized subchassis was mechanically and electrically designed to be directly interchangeable with the vacuum-tube subchassis. See Fig. 2.

The transistorized i-f section is unique, in that mechanical filters are used, providing a constant bandwidth over the complete range of input signals. See Fig. 3. Voltage stability is maintained over the range of supply variations by the use of an individual transistor-Zener diode voltage regulator, T_{17} and D_2. Also, the need for i-f neutralization is eliminated and assurance of interchangeability of transistors is made possible by the use of the grounded base connection.

The gain of the transistorized i-f strip is 90 db; this is equal to the gain of the electron tube i-f strip. The first four stages of the i-f strip are automatic-gain controlled. The bandwidths of 2-, 4- and 8-Kcps. are obtained by the use of Collins mechanical filters.

**The work in this report was done by Mr. Schwartz while employed at Lincoln Laboratory, M.I.T.

The audio amplifier consists of two grounded emitter, medium-power driver stages (T12) and (T13) driving a grounded emitter, class B push-pull power output stage (T14, T15). This section has a maximum undistorted power output of one watt at 24 volts. Provisions are made for maximum reliability of operation over supply voltage and temperature variations, and for maximum interchangeability of transistors. See Fig. 4. The audio frequency response compares favorably with the vacuum-tube audio frequency response. See Fig. 5.

The r-f AGC system of the electron vacuum-tube circuit was incorporated in the over-all AGC system. The only change in the r-f AGC system is the use of silicon diodes instead of electron-tube diodes. (D7, D8).

The i-f AGC section consists of an AGC diode, D5, and a D.C. AGC amplifier (T10). With AGC disabled, the output of the D.C. amplifier is held at a fixed reference level. This reference voltage is connected through the AGC bus to the bases of the first four i-f stages (T1, T2, T3, T4). Under these conditions, the emitter current of each of the four stages is determined by the difference of the AGC reference voltage at the base, and a fixed voltage at the emitter, divided by the value of the resistance in the emitter lead. With AGC on, an increase in signal strength causes an increase in D.C. voltage at the output of the AGC amplifier, which results in an increase in the base voltages of the controlled i-f stages.

In turn, the difference voltage between the base and emitter decreases, lowering the emitter current of each of the stages. Lowered emitter current results in increased emitter resistance, and, in turn, decreases the gain of the AGC-controlled stage. The effectiveness of the AGC is shown in Fig. 6. The output signal variation is held to within 10 db for an input signal variation of 100 db. A comparison with the electron vacuum-tube AGC system shows the transistorized version to be within 3 db for these signal level variations.

Diode D5 provides AGC delay in addition to AGC rectification. This delay is the result of the crystal end (equivalent to the cathode end of a diode) of D5 being set, with the absence of an input signal, at a more positive D.C. voltage than the point contact end. Therefore, until the input signal reaches a level sufficient to cause the A.C. signal into the AGC section to overcome this bias across the delay diode, no AGC action will take place. The amount of delay is controlled by the setting of the i-f AGC delay. With AGC operation the amount of AGC D.C. voltage output at the emitter of T10 is dependent on the amount of D.C. voltage developed at the base of T10. The D.C.

voltage is due to the rectification of the A.C. input signal by diode D5. Comparable sensitivity curves are shown in Fig. 7.

To provide for maximum beat frequency oscillator stability, the transistor BFO, T19, was built around Collins type T602, temperature-compensated tank circuits, as used in the electron tube BFO. A separate voltage regulator system for the BFO is employed (T18, D4).

The calibrator circuit is made up of transistor T22 used in a blocking oscillator circuit, and diode D10 used as a clipper to provide the proper shaping features. This circuit provides usable harmonics, up to 30-Mcps. in steps of 100-Kcps.

The squelch circuit consists of D7, the squelch rectifier, T20 a grounded-collector, D.C. amplifier in series with a grounded-emitter D.C. amplifier T21. The operation of the squelch section is as follows: with no signal input, the D.C. base current of T21 is $B_1 \times I_{co}$. The collector current of T21 is $B_1 \times B_2 \times I_{co}$, the value of which is usually less than 100 ua; therefore the relay is not energized. In this condition, the relay contacts ground the input of the audio system, so there is no audio output. With signal input the rectified D.C. voltage at diode D7 causes base current to flow in T20, which, when amplified, through T20 and T21, results in a flow of collector current sufficient to energize the relay. Operation of the relay lifts the audio input from the grounded condition, and audio output is available. The signal amplitude necessary to operate the squelch circuit is determined by the setting of the r-f gain control.

The output isolation stage, T11, provides a convenient, low-impedance i-f signal output for operation of teletype equipment.

The noise limiter (D6) and audio detector (D2) sections are identical with the vacuum-tube version except that silicon and Germanium diodes are used rather than vacuum diodes.

Three transistor-series type voltage-regulator circuits are employed using as voltage references Zener-voltage breakdown diodes. Provisions are made for good regulation and reliable operation by keeping each regulator circuit well within maximum power dissipation limits.

The total power drain of the hybrid receiver is 0.9 amperes; the total power drain of the vacuum-tube receiver is 2.7 amperes.

It should be noted here that this model is an experimental and not a preproduction model.

The author wishes to express his appreciation to Mr. Walter E. Morrow, of Lincoln Laboratory for his invaluable guidance and Mr. Dennis W. Gosselin for his part in the testing and construction of the receiver. I wish to acknowledge the fine coordinating efforts of Mr. Samuel Berger of SCEL.

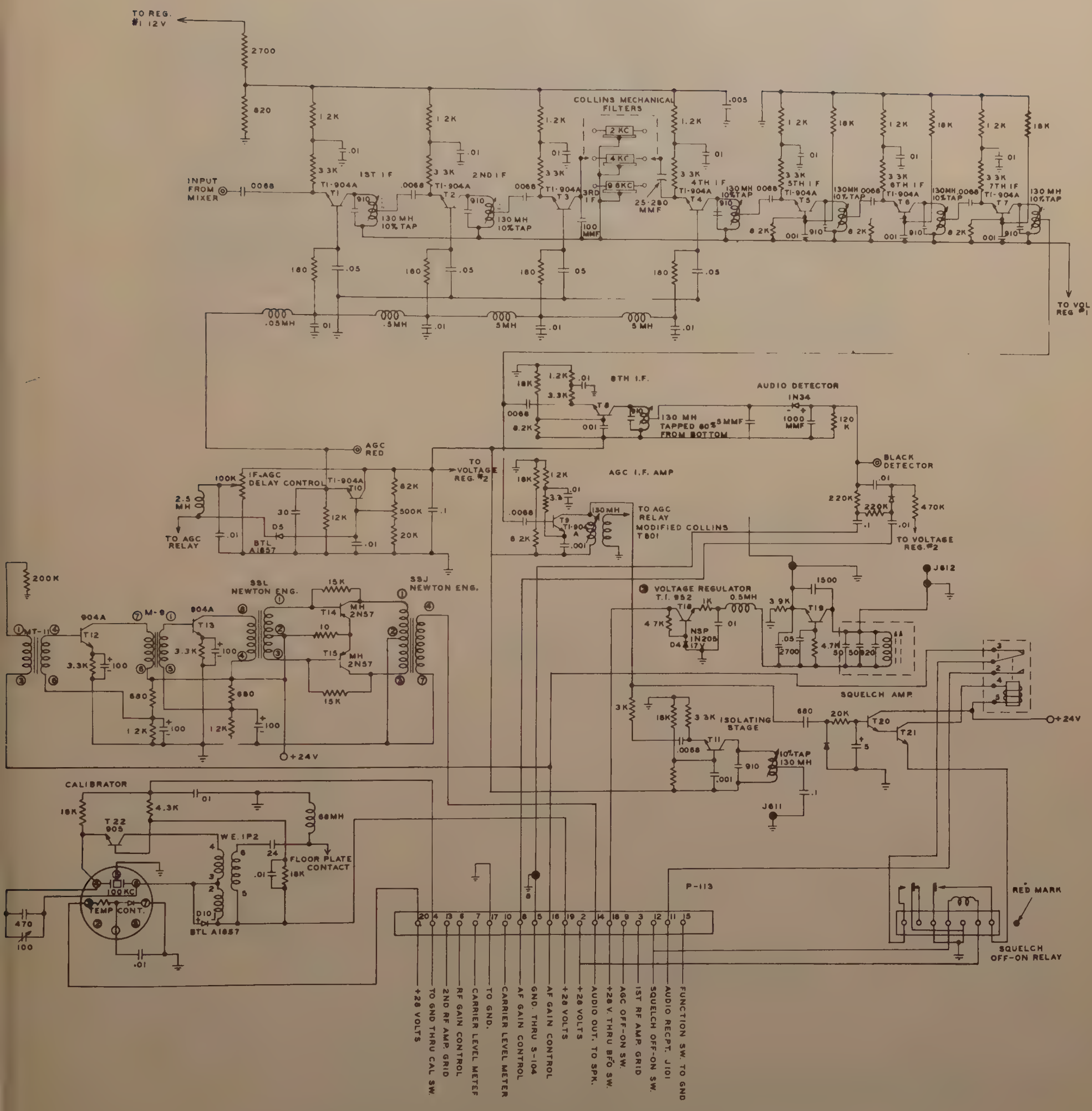

Fig. 1 - Schematic and diagram of receiver.

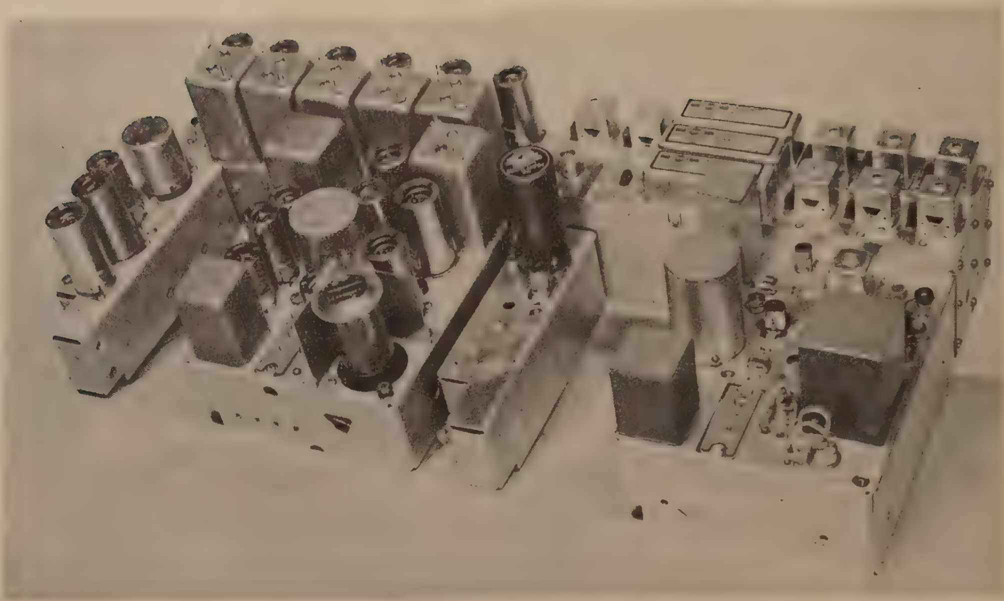

Fig. 2 - Photograph of receiver.

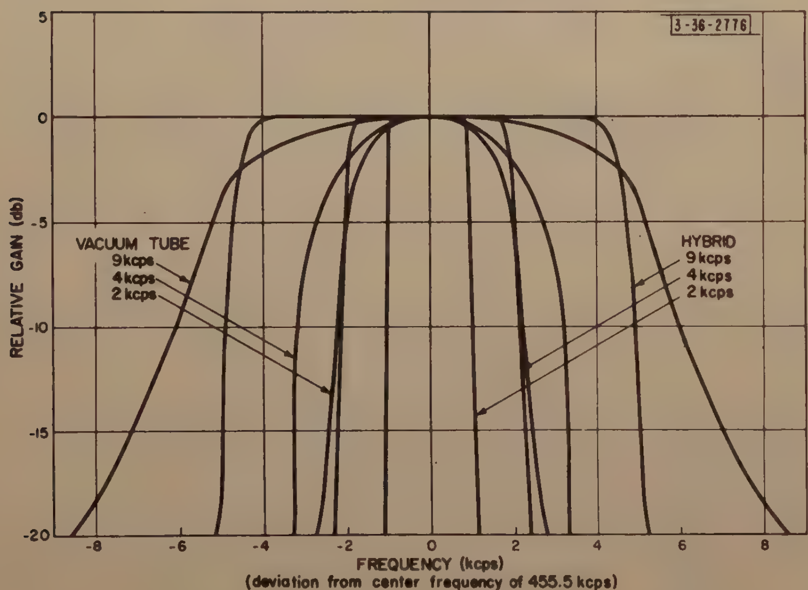

Fig. 3 - Selectivity curves of the IF bandwidth.

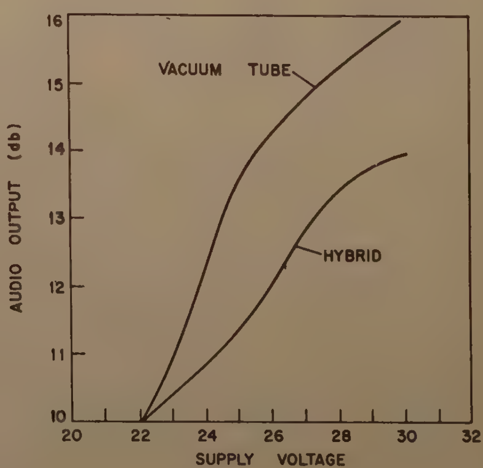

Fig. 4 - Effect of battery voltage variations on receiver performance; rf signal input 30 per cent mod. 1000 cps.

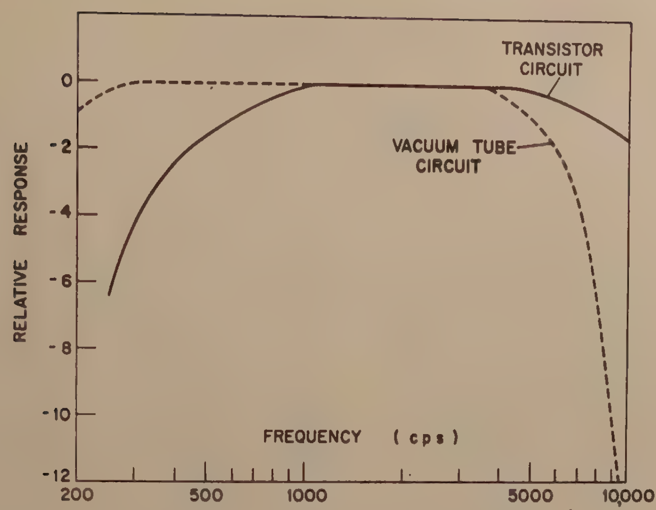

Fig. 5 - Audio frequency response.

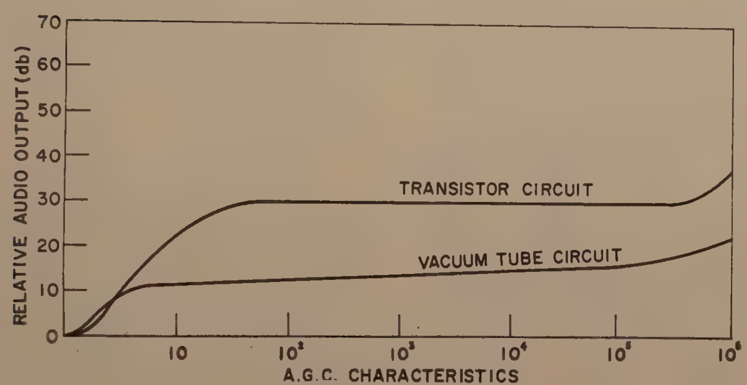

Fig. 6 - RF input signal (µv).

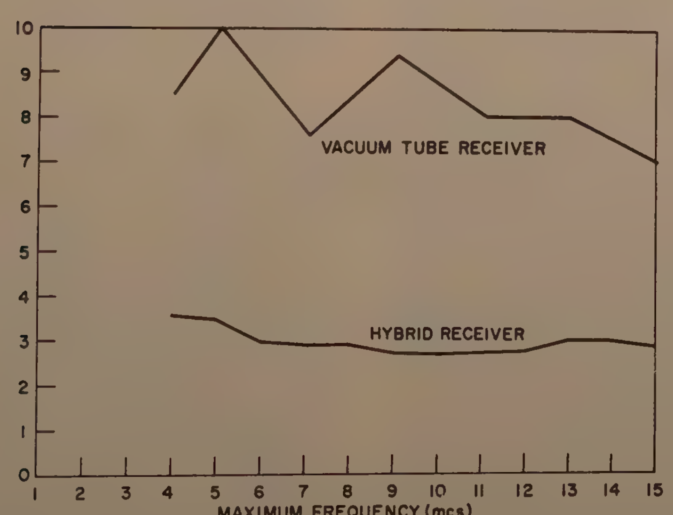

Fig. 7 - Sensitivity characteristics -- BW-(9 kc) 10 db
S + N/N at 10 mw output.

COMPARISON OF SPLIT CHANNEL FM AND SINGLE SIDEBAND FOR LAND MOBILE SERVICES

A. A. Macdonald
Motorola, Inc.
Chicago, Illinois

Recently an increasing amount of attention has been given to the use of single sideband transmission in various services. During the past few years the military have been reviewing the use of single sideband for their communication requirements. At the Hamvention in Dayton this spring, single sideband seemed to be the major topic for discussion. Recently, also, the FCC highlighted progress on single sideband communications when they requested comments on Docket 11678, implementing single sideband for airborne mobile communications services below 25 Mc.

Since the land mobile users are undoubtedly the most efficient users of the radio spectrum and are at the same time the most crowded for spectrum space, the question naturally arises as to whether or not single sideband transmission could provide an adequate service to land mobile users in the 25-50 Mc. and higher frequency bands. The corollary question of whether or not the use of single sideband transmission will actually permit a greater channel utilization in the land mobile frequency bands must also be answered. This paper will discuss some of the basic considerations involved in both split channel FM and single sideband AM transmissions. An effort will be made to compare some of the advantages and disadvantages of both systems.

First of all, it should be recognized that the growth of the land mobile services has just about kept pace with the technical advances in the field, and the land mobile services are more likely to run out of frequencies sooner than any other V.H.F. communication service. The majority of V.H.F. radio communication services are not close to the state of the communications engineering art at the present time. The land mobile services more than any other can foresee future limitation by a scarcity of communications channels. Therefore, it is evident that if single sideband transmission can provide an adequate service in land mobile frequency bands, and further, if single sideband transmission permits a greater use of the frequency spectrum, single sideband transmission will be the rule rather than the exception in the land mobile services of the future.

STATUS OF SPLIT CHANNEL ALLOCATIONS

Let's review first the present status of split channel allocations in the land mobile communications bands. In July, 1951, Commissioner Wayne Coy of the FCC, requested the JTAC to establish a Subcommittee to provide the FCC with the answers to a number of questions they posed regarding channel splitting in the V.H.F. and U.H.F. frequency bands. After a concentrated effort on the part of all members of the Subcommittee the report of the JTAC Subcommittee On Land Mobile Channel Allocations was sent to the FCC in May, 1953. In January, 1954, the Commission asked the JTAC for additional information regarding capture effect in narrow band FM systems. The JTAC replied to the FCC in December of 1954. FCC Docket 11253 on channel splitting was issued January of 1955 and received wide comment by all members of the industry. To date, however, the FCC still has not finalized rule making, even though the plea was made by many that split allocations should be made in the low band even if action was withheld in the high band. Recently the FCC has put a freeze on further allocations of split channels in the petroleum industry in the low band. This action is working a great hardship on the members of the petroleum industry who undoubtedly have more crowding than any other user except possibly the taxi industry.

Even though the FCC has withheld action on Docket 11253, the manufacturers have gone right ahead with equipment development and most manufacturers now have equipment which is capable of simple modification to split channel operation. Some equipment can be easily modified in less than 15 minutes and does not require realignment. Manufacturers have shipped split channel equipment in all bands, including the UHF band, to farsighted customers. Many of the user groups are most anxious to implement split channel communications within their field; they see this as the only way at present by which they can make more channels available.

Since the work of the JTAC in 1952, some progress has been made in the art. The frequency stability of production models of VHF and UHF equipment has been improved to the point where both receivers and transmitters are being sold which will easily meet the specifications of plus or minus .0005% over the temperature range of -30 to +60°C. Equipment is also available from one manufacturer which incorporates the modulation splatter filter recommended by the JTAC in their report. The splatter filter was recommended by the JTAC and was shown in field tests to provide appreciable reduction of the adjacent channel modulation splatter from a transmitter. At the time the JTAC report was made no quantative data was taken concerning the advantage of the modulation splatter filter. Several of my slides will show the measured reduction of modulation splatter which can be obtained by means of the filter.

Figure No. 1 shows the circuit of a transmitter incorporating the modulation splatter filter consisting of a 6 henry choke and a 390

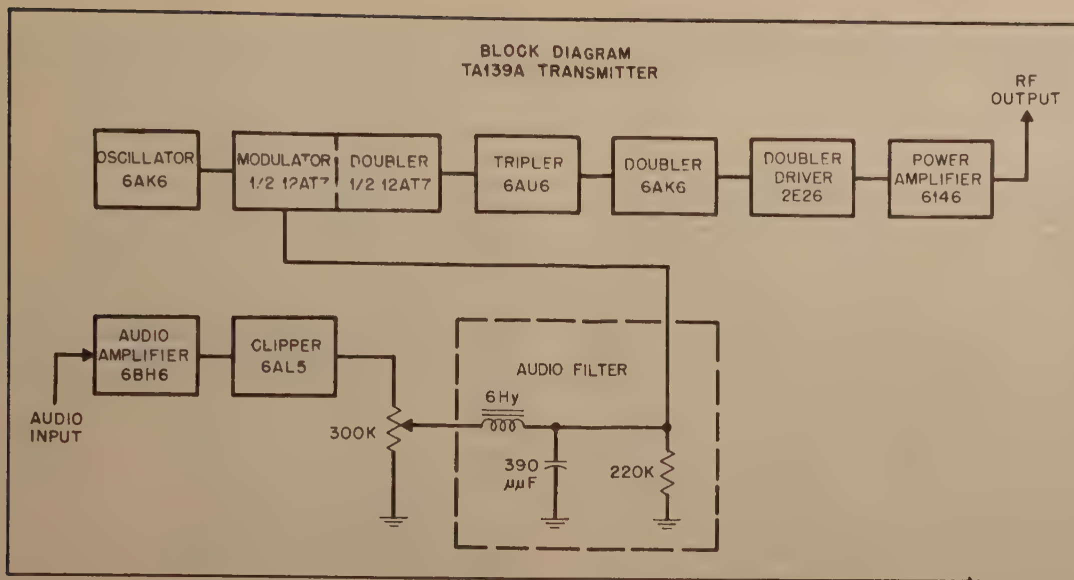

Fig. 1 - Block diagram TA-139A transmitter.

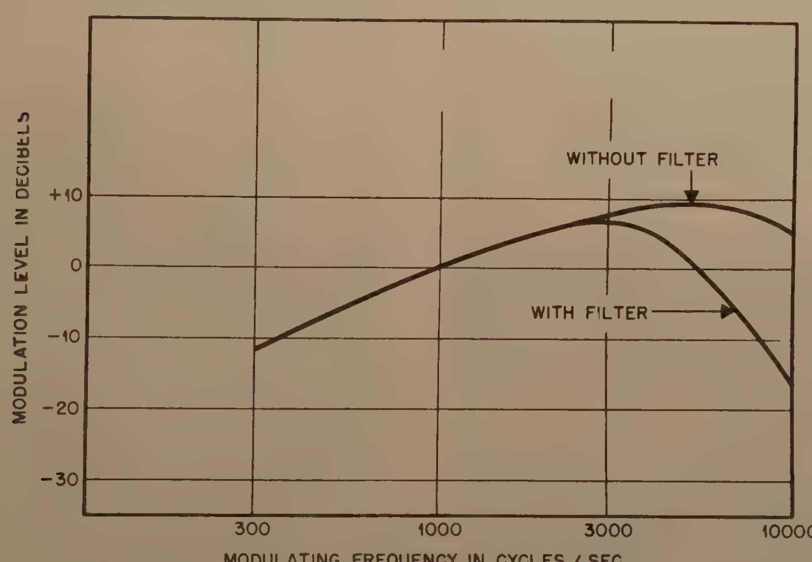

Fig. 2 - Response characteristic TA-139A transmitter.

μμf capacitor. In order to be effective the filter should be introduced between the audio amplifier and the modulator. Incidentally, tests have shown that if the transmitter is equipped with instantaneous deviation limiting as well as a modulation splatter filter, the amplitude of the modulation sidebands will be less in the adjacent channel than they would be if the circuit included only the modulation splatter filter. It should be recognized that the modulation filter is provided to prevent pre-emphasized modulation by extremely high frequency, i.e., above 10 Kc., audio and noise components which would otherwise be fed to the modulator stage. Therefore, it should be recognized that the filter circuit must be very carefully arranged so that it is not bypassed by stray capacity. A simple check on the audio response out to 10 Kc. is not adequate to show whether or not the filter is actually doing its job in the adjacent channel. In order to prove performance it is necessary to measure in the laboratory the actual sideband spectrum radiated by the transmitter, both with and without the filter.

Figure No. 2 shows the audio response with and without the filter in the transmitter. The cutoff of the filter itself is 12 db per octave. This response is shown to give you an idea of the audio response, although it must be remembered that this is not indicative of the operation of the splatter filter. In order to give you a still better idea of the improvement to be obtained by the addition of the modulation splatter filter, Figure No. 3 shows the path loss requir-

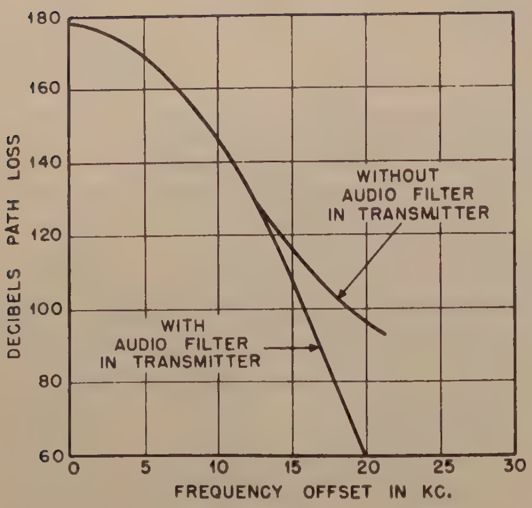

Fig. 3 - Path loss required to prevent squelch opening interference between a 30 watt transmitter and a split channel receiver v.s. frequency offset.

ed to prevent squelch opening of an adjacent channel receiver by modulation splatter, with and without the filter. The improvement is about 35 db, which reduces the interference radius from about $1\frac{1}{2}$ miles around a 30 watt low band adjacent channel transmitter to about 1000 feet.

The present status of split channel allocations in the land mobile services can be summarized by saying that split channel allocations have been proven possible and practical in all bands now occupied by the land mobile users, and industry is awaiting FCC action in assigning split channels in the V.H.F. and U.H.F. bands.

STATUS OF SINGLE SIDEBAND

Let us turn now to the status of single sideband communications. At the present time practically everybody is talking about, and quite a few people are actually working with single sideband communications. As I mentioned previously, the Hamvention in Dayton this spring devoted a great deal of its attention to the use of single sideband communications by its members. Many of the hams have developed extremely ingenious means for generating and detecting single sideband signals. As I indicated previously, the military are taking a serious look at single sideband communications for their requirements. Also, it was the airlines themselves who requested the FCC to take action on the docket implementing single sideband communications below 25 Mc. in the airborne mobile service.

For many years single sideband transmission has held promise of being a method for cramming more words per second per kilocycle into the radio spectrum. However, the problem associated with both generating and receiving a high quality single sideband signal at the higher radio frequencies has been a serious deterent to progress in single sideband communications. Two fairly recent developments, however, have greatly spurred activities in the single sideband field. In 1946, R. B. Dome developed several wide band audio phase shift networks which produce an audio phase shift of $90 \pm 3^{\circ}$C throughout the voice spectrum. These phase shift networks permit a relatively simple means of developing a single sideband signal using two balanced modulators which can be operated at carrier frequency to feed a power amplifier or an output circuit directly. These techniques have been well documented in the art. (1,2,3,5) Another popular method of developing a single sideband signal is to employ a single balanced modulator to produce both the upper and lower sidebands and suppress the carrier. Then one or the other sideband is filtered out by a sharply selective filter which will reject the unwanted sideband. The development of high quality electromechanical filters in the low radio frequency spectrum has greatly simplified this so called "brute force" method of developing a single sideband signal. The electromechanical filter permits the use of higher "Q" resonant elements, and therefore, provides a better shape factor, i.e., the ratio of the nosewidth to the skirt width at X db down.

In recent years considerable improvement has been made in the frequency stability of both receivers and transmitters. It is now possible to obtain by relatively simple means frequency stabilities in the order of 1 part per million over a temperature range of -30 to +60°C. This is an extremely important factor since the quality of the single sideband signal is completely dependent upon whether or not a specific tolerance in cycles per second can be maintained at carrier frequency. Those of you with carrier experience know that a single sideband signal which maintains a frequency tolerance of 25 cycles is fairly good. A frequency error of 50 cycles is tolerable; however, beyond 50 cycles the distortion in the signal becomes serious and severe degradation of intelligibility occurs. It is interesting to know that at 50 Mc. a frequency error of 50 cycles represents 1 part per million or is approximately that which can be held with the best techniques available to the land mobile user.

If it is not possible to obtain extreme frequency stability in the communications equipment, it is possible to transmit a pilot carrier and from it synthisize a local carrier which has the required stability, however, these techniques complicate the equipment considerably. It has been mentioned by some that it would be possible to provide the land mobile services with fairly decent stability which would in itself not be adequate to provide communications, but, at the same time, provide the mobile operator with a knob labeled "Clarifier", which he could use to produce small frequency changes which would make the communication intelligible to him. We have so much difficulty with people improperly adjusting the squelch and volume controls that I doubt that it would be wise to provide the mobile operator with a "Clarifier" control.

In summary, I believe it can be said that the techniques for providing a single sideband signal have been greatly improved within the past few years. Needless to say considerable promise exists for further improvement in the future.

COMPARISON OF SPLIT CHANNEL FM AND SINGLE SIDEBAND

At this point the far sighted engineer will say: "Now let's assume that the problems associated with the generation and detection of a single sideband signal can be satisfactorily solved; how then does the single sideband system compare with the present split channel system in the VHF services?"

Before we get very far with our comparison it is necessary to define what we mean by single sideband signal and also define what we mean by the power output of the single sideband transmitter. From the standpoint of the overall economy of equipment and the technical performance of that equipment the single sideband signal using a suppressed carrier is far superior to the single sideband signal with a carrier. Therefore, in our discussions we will be referring to a single sideband suppressed carrier system. That is a system where the carrier is suppressed about 20 db relative to the peak envelope of the sideband.

The next question is: "What do we mean when we talk about power of a single sideband transmitter?" I like the definition that was given by one of the hams in Dayton. When asked the question of what he meant when he spoke of power output, he said, "I mean the power that you light light bulbs with". Well that's what I mean too. We will refer to the power rating of a single sideband transmitter as that power transmitted during the peak of the modulation envelope. This is easier to handle than an average power definition because we would then have to ask what type of modulation was being used. What is the peak to average ratio, etc., etc. Peak envelope power is the generally accepted rating for S.S.B. transmitters.

In this comparison between FM and single sideband systems, we will be interested only in the basic electrical characteristics because I am certain that engineers will find ways of simplifying the single sideband equipment so that it is comparable to our present FM equipment.

First of all, the main advantage of single sideband over a split channel FM system is a theoretical advantage in economy of frequency spectrum. To offset this advantage we have, at present, the following disadvantages:

Cost
Size
Complexity

The absence of capture effect
Frequency stability requirements
Automatic gain control requirements
Susceptibility to ignition interference
Relatively poor performance in noisy areas

As mentioned above, we will write off, cost, size, and complexity as being factors which are under control of the development engineer. We can almost place the requirements for automatic gain control and extreme frequency stability in the same category. Certainly the requirement for a fast acting automatic gain control, having a dynamic range of 20 to 40 db, is apparent to all mobile users. It is quite possible, however, that this problem can be solved in the future, so we won't worry about it here. We have seen considerable improvement during the past few years in the basic frequency stability of all equipment, so we can expect further improvement in the future. At the present time the requirement for extreme frequency stability would be a severe problem in a single sideband mobile system in the VHF band, however, it is quite possible that this problem will considerably be reduced in the future. Let us, therefore, confine our discussion to the basic characteristics of the two systems. On the one hand we have the advantage of the single sideband system of spectrum economy, and on the other hand we have the basic disadvantages of the same system on the lack of capture effects, the performance on ignition noise, and performance in a noisy signal area.

First of all the fact that we have no capture effect in any AM system, including single sideband systems, can be a great disadvantage to us in the design of land mobile systems. The FM capture effect gives us a design latitude which cannot be obtained in any AM system design. By capture effect I mean the ability of the FM receiver to completely discriminate against a signal which is only a few db weaker than the desired signal. In an FM system when the undesired signal is about 6 db weaker than the desired signal no interference will be audible. In the AM system, and this includes single sideband AM, noticeable interference will be heard even though the undesired signal is 30-40 db weaker than the desired signal; when the undesired signal becomes only 20 db weaker than the desired signal the interference will be definitely objectionable. Therefore, in an FM system we have an advantage in that we have a means for separating a desired signal from an undesired signal; all we have to do is provide, on a systems basis, a slight advantage for the desired signal and it will capture the receiver and no interference will be heard from the undesired signal. In an AM system on the other hand, we must design the system so that there is at least 20 db protection provided or the undesired signal will be definitely objectionable, and 40 db if we wish to avoid noticeable interference. In a standard AM with full carrier, even more than 40 db protection is required if it is necessary to eliminate the carrier beat note between the desired and undesired carriers. In a single sideband AM

system, of course, the carrier beat will not be as prominent since the carrier is attenuated 20 db relative to the sideband. I think you will agree that the capture characteristic is a definite advantage in land mobile systems design.

Ignition interference, which is a problem to the majority of users of split channel FM systems will be many times aggravated when we go to single sideband AM system. You will find that ignition noise, which is a nuisance in an FM system becomes devastating in an AM system. Here again the FM capture effect works to quickly reduce the destructive interference from ignition noise to a nuisance and then to nothing as the signal is increased. On the other hand, in AM systems the same ignition noise will produce interference over a very wide range of signals. Noise limiters can help to reduce the peak interference, but they cannot eliminate it.

Now let's discuss performance in a noisy signal area. Figure No. 4 shows the relative performance of AM, PM, and single sideband systems, each rated at the same carrier power; in the case of the single sideband transmitter we are actually talking about the peak envelope power. You will note that in order to make a comparison between the PM, or phase modulation system, we use in the land mobile services and the AM systems, it is necessary to apply pre-emphasis to the transmitters and de-emphasis to the receivers in each system. It is interesting to note that due to the parabolic noise distribution in the FM or PM system, they gain 8.3 db more by pre-emphasis and de-emphasis than the AM systems, which have a flat noise spectrum. You can see from these curves that the

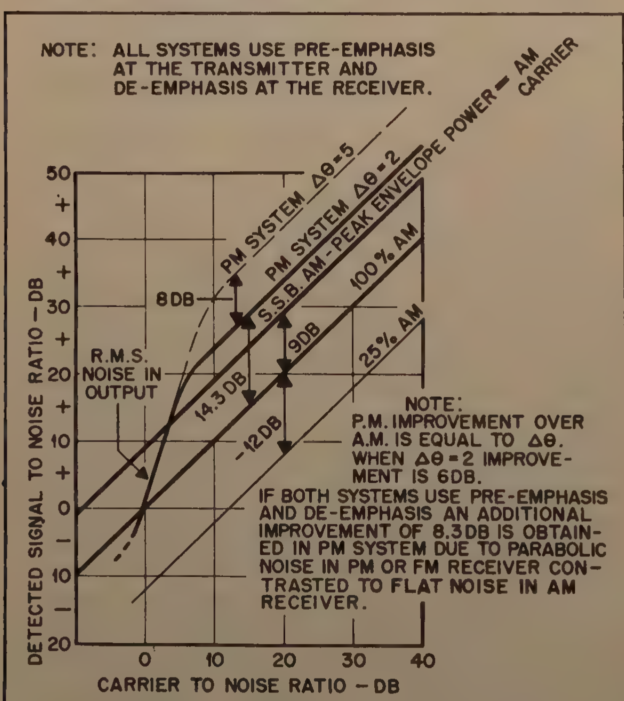

Fig. 4 - Signal to noise v.s. carrier to noise in AM, S.S.B. AM, and narrow band phase modulation systems.

single sideband AM system offers considerable advantage over the double sideband AM system, but that the split channel PM system still offers some advantage over the single sideband AM system.

An interesting note here is that the performance of the split channel PM system can be greatly improved by increasing the modulation index. In a given system which employs instantaneous deviation limiting plus the modulation splatter filter this can be done by merely talking louder into the microphone so that the average modulation is increased and, therefore, the average modulation index will be increased. It should be noted, however, that these same techniques can be applied to AM systems. I have only mentioned them here to show you how important it is to see to it that the system is properly set up, and when it is, that the operators understand the advantage of speaking directly in the microphone; and not leave it hung up on the dash while they talk from behind the wheel.

It is interesting to note from this curve that in the phase modulation system the ratio of improvement over an AM system is equal to the modulation index, in other words using FM or PM you are able to increase the modulation index above 100% modulation and therein lies the basic advantage of FM and PM over double sideband AM systems. In a single sideband system one is also able to effectively increase the modulation percentage since all of the transmitted power can be placed in one sideband. However, in the AM system one cannot obtain the immunity to impulse noise which is inherent in the FM and PM systems.

Finally, in our comparison we come to the basic advantage cited for the single sideband AM system, namely its economy of frequency spectrum; let's take a look at the picture. First, we have Fig. 5 showing the theoretical calculated sideband spectrum of a single sideband transmitter. In the picture on the left the carrier is not suppressed and we see that the sideband spectrum has appreciable amplitude over a relatively wide frequency range. On the right we have the case of the single sideband spectrum where the carrier is suppressed by 20 db. You will note the drastic improvement and narrowing of the calculated spectra. It should be noted here, however, that this analysis applies for a single tone modulation if we were to modulate this transmitter with two tones of approximately equal amplitudes the sideband spectrum would be similar to that shown on the left portion of this slide. In this analysis the distortion assumed in the single sideband transmitter was approximately 8%. It has been shown that considerably better distortion can be obtained in a single sideband transmitter on a static measurement basis.

It is said, however, that proof of the pudding is in the eating, and the single sideband proponents have been very slow to satisfy the one question which really should be asked of a single sideband system, and that is: "Is it

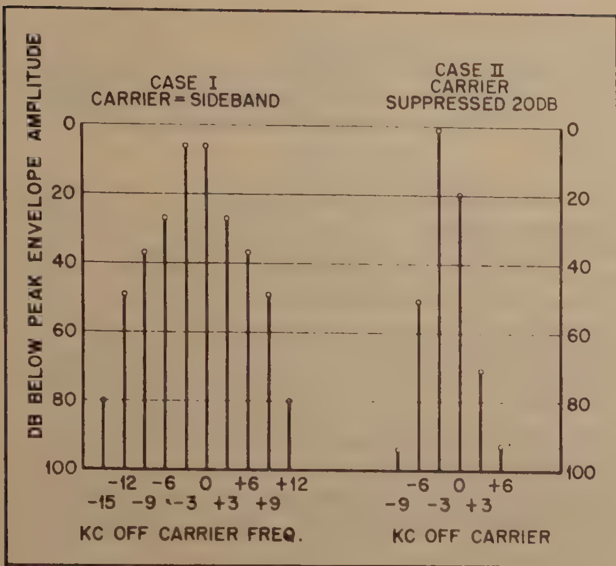

Fig. 5 - Calculated sideband spectrum of S.S.B. transmitters having 8% distortion and modulated with 3 Kc. tone.

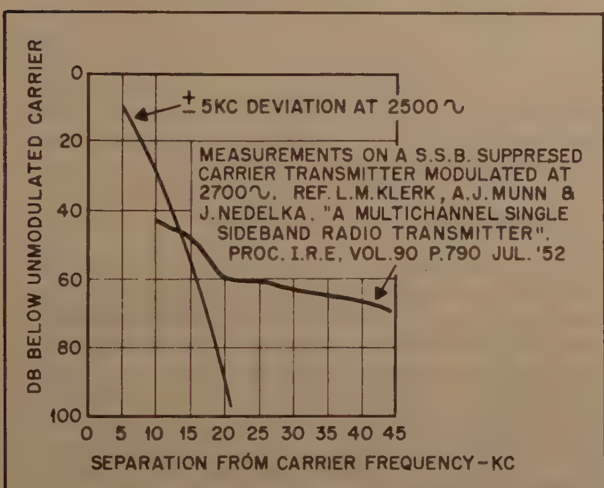

Fig. 6 - Comparison of measured modulation envelopes of a single sideband AM transmitter v.s. a P.M. transmitter with ± 5 Kc. deviation.

economical of frequency spectrum?" Figure No. 6 shows a comparison of a split channel FM modulation sideband spectrum and a single sideband transmitter which was measured by the Bell Telephone Labs. The data for this curve was obtained from an article in the I.R.E.[6] The equipment on which the data for the single sideband transmitter was taken was the best available at the time that the article was written. The overall transfer characteristic showed a distortion of less than 2%. You should note that the single sideband transmitter is very economical of spectrum at frequencies less than about 13 Kc., however, beyond 13 Kc. the split channel FM system produces very little interference, however, the single sideband transmitter has an appreciable modulation splatter on out to 45 Kc. and more.

These are the only measured data I have seen. However, recent articles by hams indicate that modulation splatter down 50 db is good!

If modulation splatter in an S.S.B. system is only down 60 db in the adjacent channel, this splatter would produce serious desensitization of a single sideband receiver on the adjacent channel even if the receiver were located five miles away. Naturally, as more and more stations are located in a given area, each of them producing modulation splatter at frequencies well removed from their assigned frequency, the modulation splatter adds up to produce a man made masking noise level which reduces rather than increases our ability to communicate. Mobile users should not step blindly into this trap.

It appears then, that one of the basic questions which single sideband proponents must answer is: "Is your system in actual fact as economical of frequency spectrum as a mathematical analysis would indicate?" Until this question is satisfactorily answered by actual test, there is very little point in talking of the frequency economy of single sideband for the land mobile services, because you would probably not be able to put any more stations into a given metropolitan area than you can now do with a split channel PM system. The split channel PM system shows a marked superiority in performance over a single sideband system. Please do not infer that I am against single sideband, definitely I am not. However, I have tried to indicate that before we all jump into the single sideband-wagon there are some very pointed questions which must be answered.

OTHER POSSIBILITIES FOR ADDED CHANNELS

Even if single sideband does not now provide a means for obtaining more useable channels in the land mobile services, there are other possibilities in addition to channel splitting which show definite promise.

First, there is the possibility of obtaining land mobile allocations in the 890-940 Mc. band. Recent propagation tests which have been conducted by Motorola and reported elsewhere show that this band shows definite possibilities for expansion of land mobile communications.

Another definite possibility for the future growth of land mobile communications is the further use of geographic channel allocations. At the present time many channels could be made available in our communications bands by geographic allocations. Of course, this requires the full cooperation of all the user groups.

Still another possibility is the use of channel offsetting which can in many cases prevent capture interference in adjacent geographic areas. If channel offsetting can be used on a systems basis to prevent capture in the FM system, new developments such as the Motorola "PRIVATE LINE" radio can be used to reject the remaining nuisance interferences which would exist

in a channel offsetting system. A great deal of work can be done on a systems basis along these lines. This work will result in the freeing of many channels; however, again, in order to accomplish this result, it will be necessary to obtain the cooperation of the various user groups.

I have here several figures which show the advantages which can be obtained by channel offsetting. Figure No. 7 shows the protection

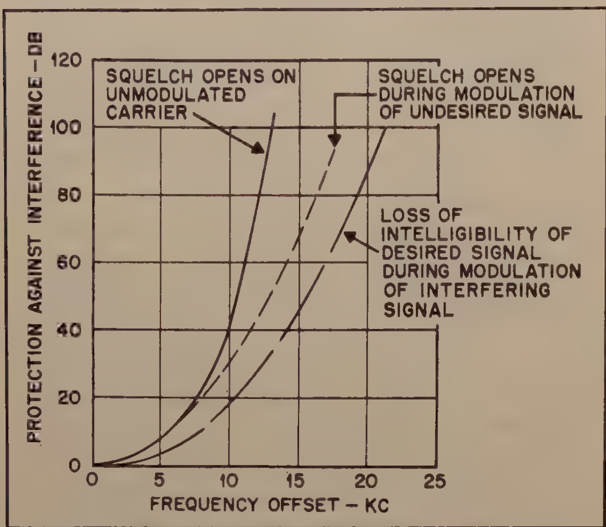

Fig. 7 - Interference protection v.s. frequency offset in a split channel system using audio filter in transmitter and I.D.C.

provided against three types of interference as a function of the frequency offset. The curve on the left shows the protection afforded against squelch opening on an unmodulated carrier. The curve in the middle shows the protection afforded against squelch opening on a modulated carrier. The curve on the right shows the protection afforded against interference by voice modulation of the undesired carrier destroying the intelligibility of the voice modulation of the desired carrier.

The next two figures show the geographic spacings required between stations to prevent destructive interference during voice modulation by voice modulation of the undesired carrier, as a function of frequency offset. Figure No. 8 shows the spacing required between base stations and Figure No. 9 shows the spacing required between base and mobile stations. In each case the dotted curves show the advantages to be gained by our friend the modulation splatter filter. It can be seen that an offset of 10 or 15 Kc. can provide considerable protection against capture interference, particularly in the case of the mobile working against a base station.

By the techniques of geographic space and channel offset, and with the aid of Motorola "PRIVATE LINE" radio or conventional selective calling systems, it is possible to design mobile radio systems in adjacent areas which will not mutually interfere with each other, but which will be able to communicate on the same or offset channel frequencies. These techniques can lead to considerably greater use of available land mobile channels. It is important to note here that S.S.B. is not suitable for most selective calling systems.

CONCLUSION

In conclusion, it can be said that many of the land mobile users are impatiently awaiting action by the FCC on the Split Channel Docket. Manufacturers in the industry have provided

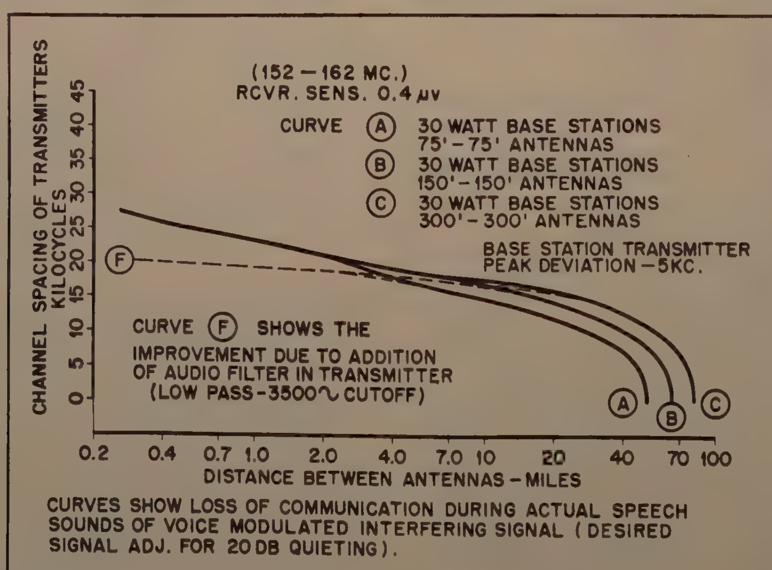

Fig. 8 - Adjacent channel interference as a function of channel spacing and antenna separation - base station v.s. base station.

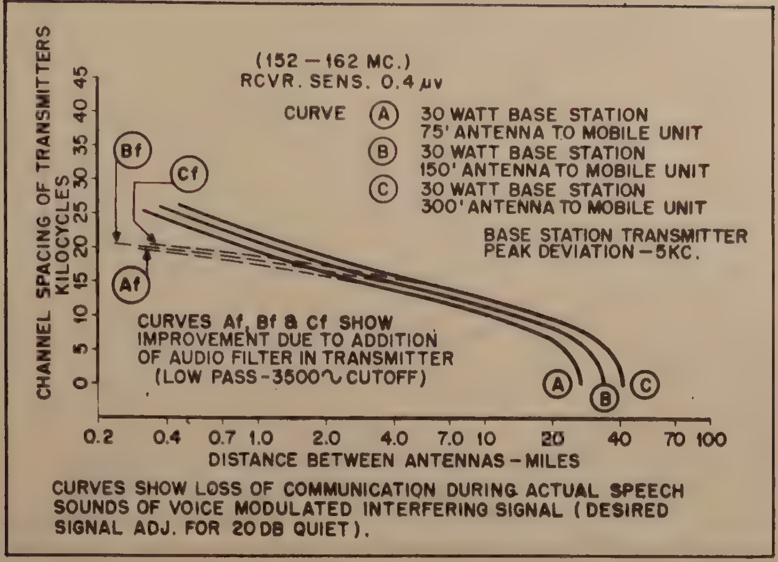

Fig. 9 - Adjacent channel interference as a function of channel spacing and antenna separation - base station v.s. mobile.

equipment which is capable of operation on a split channel basis in both the high and low V.H.F. bands and also in the 450 Mc. U.H.F. band.

At the present time single sideband leaves many questions unanswered with regard to application in the land mobile services. However, one prime question which remains unanswered and which must be answered before we jump on the single sideband-wagon is: "Is single sideband actually able to provide economy of the frequency spectrum."

Comparison between split channel FM and single sideband shows that split channel FM shows a definite advantage to the user. This advantage occurs in capture effect, in greater immunity from impulse noise, and in more noise free performance within the basic coverage area.

Even if single sideband is not ready today to serve the land mobile services, there are other bands and other techniques which can open up a large number of channels not now being used.

Finally, I would like to say that I have the greatest confidence that engineers will, to steal a phrase from Curt Plummer, find ways to permit more communications per second per cycle in the land mobile frequency bands.

Bibliography

1. M. A. Honnell - "Single Sideband Generator" Electronics November 1945 p. 166
2. R. B. Dome - "Wideband Phase Shift Networks" Electronics December 1946 p. 112
3. O. G. Villard - "A High Level Single Sideband Transmitter" Proc. I.R.E. November 1948, Vol. 36 p.1419
4. J. N. Brown - "Commercial Aspects of Single Sideband", Parts I and II Radio and Television News, May-June 1956
5. D. E. Norgaard - "S.S.B. Jr." General Electric Ham News, Nov.-Dec. 1950
6. L. M. Klerk, A. J. Munn and J. Nedelka - "A Multichannel Single Sideband Radio Transmitter" Proc. I.R.E. Vol. 90 P-790, July 1952